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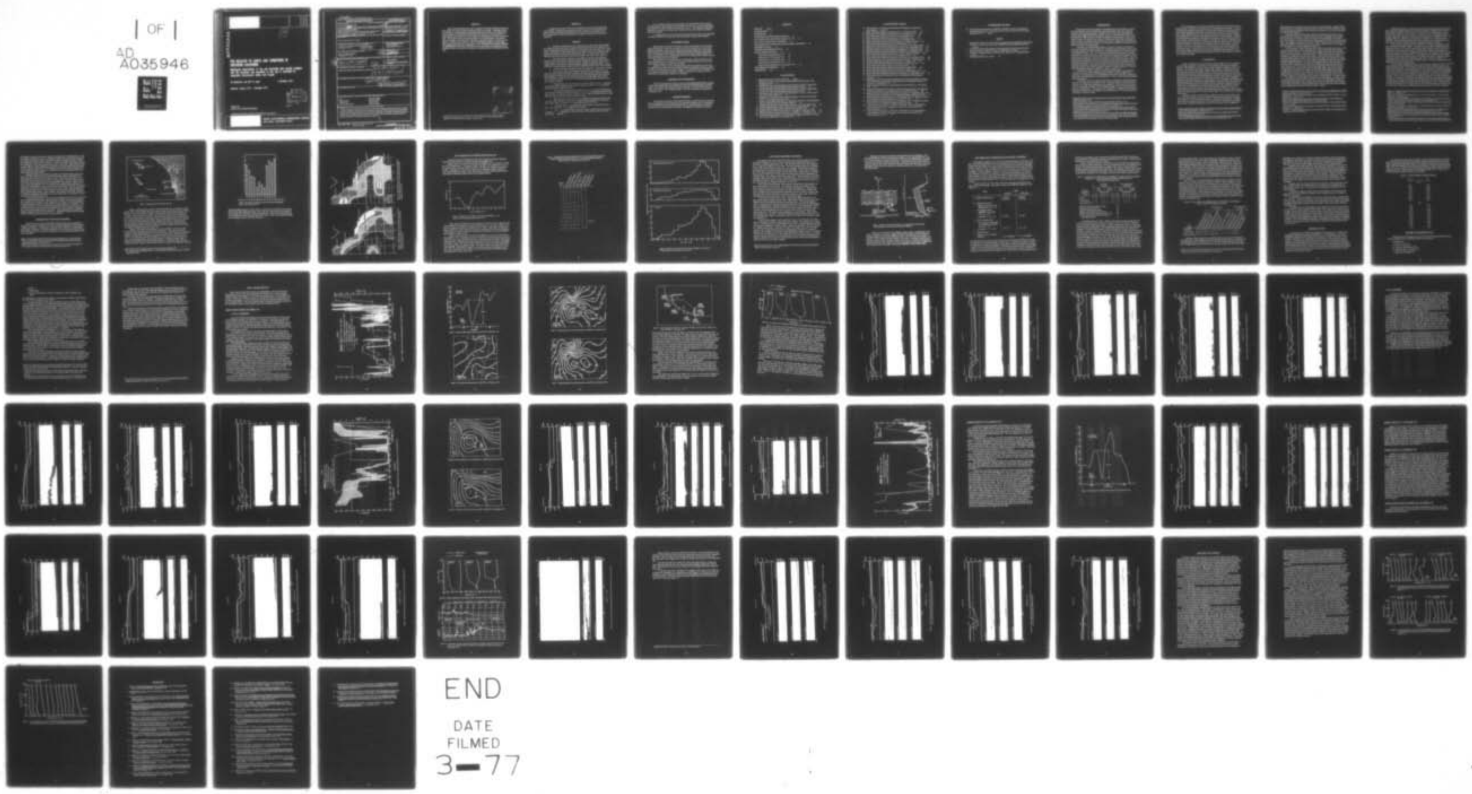

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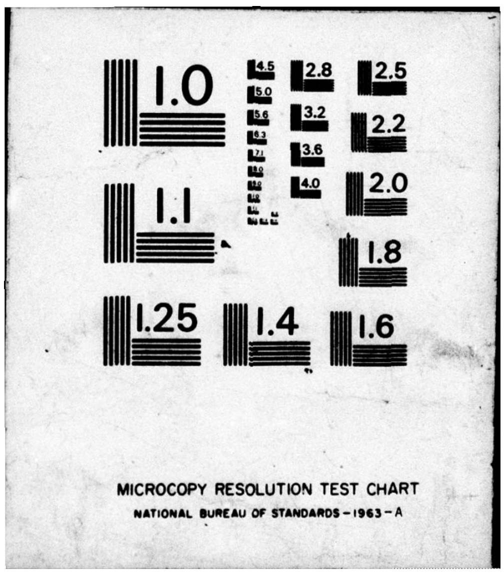
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FOG RELATED TO SANTA ANA CONDITIONS IN SOUTHERN CALIFORNIA

Multisensor observations of fog and mesoscale data provide evidence that the formation and movement of the fog is controlled by mesoscale low-pressure eddies and troughs

VR Noonkester and AGC LE Logue

5 November 1976

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Many fog events have been observed at the coast of San Diego during the weakening of Santa Ana conditions in Southern California. The events have been observed by remote (eg, FM-CW radar and acoustic echosounder) and direct (eg, radiosonde) atmospheric sensors. The sensor observations and analysis of mesoscale data provide evidence that the formation and movement of Santa Ana-related fog is controlled by mesoscale low-pressure eddies and troughs. The fog is always capped by an inversion.

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PREFACE

Marine fog investigations have been in progress at the Naval Electronics Laboratory Center since 1974, using a coastal multisensor system at San Diego. Although the pertinent physics and meteorological-oceanographical elements are likely to be similar for all fog occurrences, the data analysis has proceeded by dividing fog occurrences into two types, namely fog associated with stratus clouds and fog associated with Santa Ana conditions. The results of the marine fog investigations are being discussed in two separate reports according to these fog types. This report considers fog related to Santa Ana conditions. An earlier report (NELC TR 1989)* considered fog related to stratus clouds. Both reports contain identical information from the INTRODUCTION through SENSORS and SUPPORTING DATA (see CONTENTS), so that each report is complete and can be examined without the necessity of acquiring the companion report for supportive information.

*Naval Electronics Laboratory Center Report TR 1989, *Fog Related to Stratus Clouds in Southern California*, by VR Noonkester and LE Logue, 12 August 1976.

OBJECTIVE

Investigate the structure of the lower atmosphere in the mesoscale region using remote sensors. In particular, investigate the nature of marine fog occurring along the coast of Southern California using measurements by the unique set of sensors at the NELC coastal site and relate the observations to methods of improving fog forecasting techniques.

RESULTS

1. The NELC coastal sensor site has proved to be a good site to observe marine fog. Many cases of fog have been observed by the multiple sensor system during the two primary fog-producing atmospheric conditions, namely stratus cloud and Santa Ana weather regimes. This report considers observations of fog related to Santa Ana conditions occurring primarily during the months from November to April. An earlier report (NELC TR 1989) discussed observations during fog events associated with stratus-cloud conditions.

2. The sensors used in this study were capable of revealing many important features of marine fog episodes. Both the acoustic echosounder and the FM-CW radar revealed the depth and structure of the marine layer; the lidar or ceilometer observed low ceilings related to fog; and the visiometer measured visibility during fog episodes. A new method of recording ceilometer output provides considerable details of the cloud-fog height.

3. All observed Santa Ana-related fog has been capped by a temperature inversion.

4. Fog related to Santa Ana conditions is observed at the sensor site in many spatial structural forms, but at least two distinct types are observed, namely fog passing over the sensors from the west like a frontal structure and fog moving up the coast from Baja California as a low deck. The frontal types are up to about 200 m thick and the deck types are up to about 50 m thick. Other spatial structural forms are observed, but are not readily classified.

5. Characteristics of the acoustic and radar echoes suggest that Santa Ana-related fog is present beneath relatively weak, low-level temperature inversions near a moving or changing mesoscale circulation pattern.

6. The minimum visibilities during Santa Ana fog are less than the minimum visibilities during stratus cloud fog, which indicates the presence of continental aerosols during Santa Ana fog. An air-parcel trajectory analysis of air arriving at San Diego during a frontal fog event indicated that the air had a continental origin.

7. Mesoscale analyses of surface weather conditions in Southern California indicate that cyclonic eddies are often present along the coast during Santa Ana conditions. These eddies appear to control the formation and movement of the fog.

8. A spatially dependent model appears to be necessary to explain Santa Ana fog. Subtle mesoscale variations appear to be important.

9. Climatological data for North Island, San Diego, indicates that Santa Ana fog occurrence is almost independent of time after sunset. This indicates little dependence on the solar heating cycle.

10. An analysis of objective fog forecasts at the Naval Weather Service Facility at North Island for fog-conducive days (days when fog is observed or forecast) shows that the success rate for their forecasts was 53 percent for 1975. The analysis is continuing to determine the importance of trends in the objective factors and to evaluate the critical values of the factors.

11. Improvements in fog forecasting in Southern California appear to be dependent on mesoscale studies for fog associated with stratus clouds or Santa Ana conditions.

RECOMMENDATIONS

Studies should be designed to measure the horizontal variability of the important fog-producing factors in the mesoscale range and then to determine how the new knowledge can be applied to daily fog forecasting using regularly available data. The studies should exploit new measuring devices including electro-optical and particle-measuring devices. A combination of coordinated measurements from aircraft, ships, satellites, and ocean buoys should provide a comprehensive data base to determine the mesoscale features influencing fog formation and dissipation.

The reliability of fog forecasts should be determined in other important areas of Naval operations so that an assessment of the fog forecasting problem can be made and proper studies designed to improve fog forecasting.

Significant advances in the understanding of marine layer behavior off the coast of California are not expected until dynamical models are developed and used in conjunction with a comprehensive measurement program. The models should be developed to aid in the design of measurement programs. Progress is expected to be tedious until joint theoretical and measurement programs are completed.

ADMINISTRATIVE INFORMATION

This work was performed under Air Task A370370C/003A/4R03302001, Element 61153N, Project WR03302, Task WR0330200 by members of the Propagation Division (NELC Code 2200) for the Naval Air Systems Command. This report covers work performed from January 1974 through December 1975 and was approved for publication 5 November 1976.

ACKNOWLEDGMENTS

The authors are indebted to DR Jensen, ML Phares, and WK Horner for their diligence in operating the sensors during the fog measurement periods and to JS Woodward and L Kincheloe for the careful processing of the data. Special thanks are extended to JH Richter for providing continuous guidance and suggestions throughout the project.

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INTRODUCTION

Marine fog creates naval problems concerning aircraft carrier operations, coastal and port navigation, aerial reconnaissance, target identification, task force maneuvers, rendezvous, and optical propagation. Wheeler (1974)[1] has reviewed some significant wartime naval engagements seriously affected by fog, and has listed general naval operations affected by fog and ship and aircraft accidents for which fog was a cause or contributory factor. He has given the number of fatalities and cost estimates of damage to ships or aircraft for accidents associated with fog. His data suggest that improvements in marine fog forecasting can save many lives and dollars and are likely to increase the probability of success of naval operations.

According to the Meteorological Glossary,[2] fog is an "obscurity in the surface layers of the atmosphere which is caused by a suspension of water droplets, with or without smoke particles, and which is defined, by international agreement, as being associated with visibility less than 1 km." For operational considerations, fog intensity is usually measured by the horizontal visibility when restricted by suspended water droplets. Hence, marine fog is associated with the sea and its intensity is measured by visibility. Based on microphysical considerations, fog may be classed as ice fog, supercooled fog, or warm fog. Warm fog (air temperature $> 0°C$) poses the greatest threat to naval operations (Naval Air Systems Command 1970)[3] and is the type of fog considered in this study. For the purposes of this study, a fog episode is associated with the events prior to, during, and following a period of time when an observer indicates a visibility restriction by "fog" or when an instrument indicates a visibility of 1 mile (1.6 km) or less.

The Navy has need to improve the climatological data base on the world-wide occurrence of marine fog for planning purposes and fog forecasting capabilities for operations. The improvement of the climatological data base for the Navy is being pursued by the Naval Postgraduate School (Renard et al, 1975),[4] other Government facilities, and civilian agencies.

An accurate fog forecast would include details concerning the three-dimensional structure of visibility and its change with time. The requirements on forecast accuracy obviously vary considerably depending on the application. Verifications of naval fog forecasts are not generally available but the forecasting capability of the time-space details appear to be inadequate.* This apparent lack of capability is considered to be primarily caused by insufficient basic knowledge and meteorological data, and not generally from weaknesses in forecasters' skills.

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[1] Wheeler, SE, *Marine Fog Impact on Naval Operations*, Thesis, Naval Postgraduate School Report NPS-58Wh74091, September 1974

[2] Meteorological Glossary, edited by DH McIntosh, Chemical Publishing, New York, 1972

[3] Naval Air Systems Command (Research and Technology Group), *Research Prospects (Marine Fog Science and Engineering)*, prepared under Contract No N66001-70-C-0713, April 1970

[4] Renard, PJ, RE Englebretson, and JS Daughenbaugh, *Climatological Marine-Fog Frequencies Derived from a Synthesis of the Visibility-Weather Group Elements of the Transient-Ship Synoptic Reports*, Naval Postgraduate School Report NPS-51Rd75041, April 1975

*Studies to determine the fog-forecasting skill scores for all naval forecasting units might reveal significant climatological geographic dependent variations in forecasting capabilities. These results could be used as an aid in the determination of the type of research most likely to improve fog forecasting and in the selection of regions where forecasting improvements are most urgently needed.

The atmospheric and ocean surface conditions conducive for fog formation or dissipation involve a continuum of processes from the macroscale (synoptic scale, ~ 3000 km) to the microscale (particle interaction). The macroscale conditions controlling the general moisture and condensation nuclei distribution provide the setting for the microscale processes. Subtle changes associated with mesoscale circulation and ocean surface conditions (⩾ 300 km) appear to create the final important processes for fog conditions. Continuous and simultaneous measurements of mesoscale and microscale features associated with fog must be made to fully understand the physics of marine fog. However, independent measurements using either scale can provide important insight into fog processes. This report describes the results of continuous measurements by remote sensors during marine fog episodes on the coast of San Diego and the interpretation of the sensor data relative to mesoscale processes. The remote sensor data were supplemented by intermittent mesoscale surface (standard observations) and upper air (radiosonde observations) data. The results indicate that mesoscale processes associated with marine fog episodes are significant and complex but tenable.

BACKGROUND

In 1931, JB Anderson[5] presented results of aircraft flights over the ocean region near San Diego pertaining to velo clouds,* fog, temperature structures, and humidity structure. He identified two types of fog occurring in Southern California: namely, fog related to velo clouds and fog related to Santa Ana conditions. He indicated that the velo-cloud tops must be below about 1200 feet (304 m) for fog to form by cloud-base depression and stressed the potential importance of radiational cooling at the top of the clouds. He did not offer any phenomenology for Santa Ana-related fog but indicated that the marine layer (cool moist layer of air below the warmer, drier air above created by subsidence) was usually present a few miles offshore and was essentially unmodified during Santa Ana conditions. He found the region below the velo-cloud top to be conducive to mixing and that inversion does not create the clouds. Sea-surface temperature was indicated to be an important factor in forming stratus and fog. He concluded by stating "there appear to be no good reasons why, with additional knowledge, not only the height and thickness of the clouds and the height of the base, but also the other features which are of vital importance to the aviator and navigator will be forecast with confidence and accuracy."

Petterssen (1938)[6] concluded that fog related to stratus was not a direct result of the cool water along the coast. The depth of the layer and mixing below the layer were found to be the most important features to consider in fog formation. Instability below the fog or cloud top (at the top of the marine layer) was found to be a predominant feature. Radiational cooling from the top of the cloud or fog was suggested as

[5] Anderson, JB, "Observations from Airplanes of Cloud and Fog Conditions along the Southern California Coast," *Monthly Weather Review*, p 264-270, July 1931

[6] Petterssen, S, "On the Causes and the Forecasting of the California Fog," *Bulletin of the American Meteorological Society*, v 19, p 49-55, 1938

*The stratus clouds which drifted overland from the ocean each night and dissipated each day during the summer months in Southern California were called velo clouds by Californians in 1931.

being important to the maintenance of the inversion and the instability. Leipper (1948)[7] found that some of Petterssen's conclusions were not valid for all years because his sample size was inadequate and presented data showing the importance of sea-surface temperature in stratus and fog formation.

Neiburger (1944)[8] concluded that radiational cooling from the stratus top was important for the maintenance of mixing below the cloud. He suggested that investigations to determine the long-term (days) and short-term (diurnal) depth of the marine layer were necessary to improve forecasts of weather associated with the stratus and marine layer. This suggestion was supported by Blake (1948)[9] who found that the inversion base-height and maximum surface temperatures were closely related and that this relationship was most likely to be caused by large-scale subsidence.

In 1948, Leipper (1948)[10] presented data on Santa Ana-related fogs and gave some objective guides/indices for forecasting these fogs. Santa Ana fogs had been generally ignored in previous research. Leipper discussed the stages of the Santa Ana fog formation and showed the significance of his forecast indices. These indices were also found to be applicable to summer-type fogs related to stratus. They are still used by forecasters at the Naval Weather Service Facility at North Island, San Diego. An evaluation of the fog-forecasting skill resulting from using these indices at North Island is given in FOG FORECASTS AT NORTH ISLAND. In a more comprehensive report on this investigation, Leipper (1948)[11] emphasized the importance of radiational cooling from the top of the fog or stratus cloud. He states that this cooling would explain "why isolated patches of fog over the sea could be colder than the underlying surface when the air outside of the fog patch is warmer than the surface, why the lapse rate through the fog is super-adiabatic, why a layer of fog once formed can move over warmer water without dissipating, and why a radiation index (a measure of the moisture gradient of the air above the fog) is important in determining the probability of fog formation." He further states ". . ., in many cases a cold surface is needed for the initial formation of fog or stratus, but after formation radiation maintains the cloud in spite of other adverse conditions." These results encouraged Leipper to suggest that most of the California stratus is formed by the lifting of fog banks. He again stresses these ideas in a later paper when discussing fog and smog banks in Southern California (Leipper, 1968)[12].

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[7] Leipper, D, "California Stratus Forecasting Correlations," 1935 and other years, *Bulletin of the American Meteorological Society*, v 29, p 294-297, 1948

[8] Neiburger, M, "Temperature Changes During Formation and Dissipation of West Coast Stratus," *Journal of Meteorology*, v 1, p 29-41, 1944

[9] Blake D, "The Subsidence Inversion and Forecasting Maximum Temperature in the San Diego Area," *Bulletin of the American Meteorological Society*, v 29, p 288-293, 1948

[10] Leipper, D, "Fog Development at San Diego, California," *Sears Foundation: Journal of Marine Research*, v 8, p 337-346, 1948

[11] Leipper, D, *Fog Forecasting on Coasts*, final report on the Fog Project, Office of Naval Research, Contract No N6oni-111, 31 August 1948

[12] Leipper, D, "The Sharp Smog Bank and California Fog Development," *Bulletin of the American Meteorology Society*, v 49, p 354-358, 1968

Although the literature on California stratus and fog decreased after about 1950, there were a number of studies related to the stratus-fog conditions. Edinger (1959, 1963)[13-14] showed that the destructive modification of the marine layer moving inland is a combination of terrain effects and surface heating. The severe control on the properties of the invading marine layer upon land by the terrain was clearly shown in Justham (1974)[15] who critically analyzed the motion of the marine layer far inland into a valley in Northern California. The marine layer depth along a coast was shown to be controlled by the synoptic pattern in the San Francisco region by Fosberg and Schroeder (1966).[16]

Advancement on the theory of the formation of the inversion capping the marine layer was made by Neiburger (1960).[17] He showed that the major characteristics of the temperature structure in the eastern Pacific Ocean near California are caused by large-scale subsidence in the eastern portion of the subtropical high. Changes in the depth of the marine layer off the coast of Los Angeles were found to be up to 500 feet (160 m) during the day by Edinger and Wurtele (1971).[18] They found that the offshore islands created appreciable wave structure downwind when the stability was suitable. They also outlined a dynamical model of the lower atmosphere which could be pursued to further our understanding of the marine layer and overlying inversion. This model included horizontal gradients and moving synoptic patterns.

Recent studies on California stratus and fog by Calspan Corporation (1974, 1975)[19,19a] using the research ship ACANIA and aircraft observations have revealed a number of important features, namely: (a) the marine air must be "conditioned by turbulent exchange of heat and moisture with cold underlying water" before fog can be formed; (b) widespread fog has been observed to occur at the surface by a depression of the base of stratus clouds; (c) fog can form in cool, nearly saturated air advecting over warmer water; (d) radiative cooling at the top of thin fog promotes the upward development of the fog and creates an inversion of temperature at the fog top; (e) widespread fog can be associated with mesoscale convergence; (f) fog patches have been observed upwind (westward) of large-scale fog-stratus systems; and (g) bay fogs are associated with the land sea-breeze system. They found that all fogs were associated with a capping inversion and cooling by long-wave radiation at the top of the fog. The process by which fog is created when the stratus base is depressed

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[13] Edinger, JG, "Changes in the Depth of the Marine Layer over the Los Angeles Basin," *Journal of Meteorology*, v 16, p 219-226, 1959

[14] Edinger, JG, "Modification of the Marine Layer over Coastal Southern California," *Journal of Applied Meteorology*, v 2, p 706-712, 1963

[15] Justham, SJ, *The Spatial Distribution of Fog/Stratus in Northern California, A Descriptive and Statistical Analysis: Summer, 1970,* thesis, University of Illinois at Urbana-Champaign, 1974

[16] Fosberg, MA and MJ Schroeder, "Marine Air Penetration in Central California," *Journal of Applied Meteorology*, v 5, p 573-589, 1966

[17] Neiburger, M, "The Relation of Air Mass Structure to the Field of Motion Over the Eastern North Pacific Ocean in Summer," *Tellus*, v 12, p 31-40, 1960

[18] Edinger, JG and MG Wurtele, *Marine Layer Over Sea Test Range*, final report for Commander Pacific Missile Range, Contract N123(61756)56992A, Pacific Missile Range Report TD 71-2, 1971

[19] Calspan Corporation, *The Microstructure of California Coastal Stratus and Fog at Sea*, Second Annual Summary Report on Project Sea Fog, prepared for Naval Air Systems Command, Contract No N00019-74-C-0045, July 1974

[19a] Calspan Corporation, *Marine Fog Studies off the California Coast*, Third Annual Summary Report on Project Sea Fog, prepared for Naval Air Systems Command, Contract No N00019-75-C-0053, March 1975

((b) above) is considered to follow a sequence of processes in the following order: radiative cooling at the top of the cloud → increase of liquid, water content at the cloud top and creation of turbulent mixing → fallout and turbulent transport of moisture, drizzle and droplets downward to below cloud base → increase of humidity below the cloud base until saturation → cloud base approaches the ground to form fog. These findings provide excellent support of earlier findings and hypotheses on California coastal fog and should form the basis for further studies. The Calspan studies did not include information on a type of Santa Ana-related fog which is a significant type of fog appearing south of Los Angeles during the winter months.

Important studies on the California inversion and associated stratus and fog conditions are being conducted by San Jose State University using the instrumented TV tower at Mt Sutro in San Francisco (Miller, 1975).[20] The tower, with a base at 254.3 metres MSL, has sensors at six levels up to 473 metres MSL. The basic sensors include wind (three vectors), temperature, wet bulb temperature, and pressure. Using the tower data to study fog, Goodman (1975)[21] determined the variations in the drop-size distribution and concentration for several fog events and found that these factors were strongly dependent on the surface air trajectory (over land or sea or both). She found that the upper boundary (near stratus or fog top) played a crucial role by supporting radiational cooling and mechanical mixing. These processes create droplets which settle as drizzle or are turbulently transported downwind to lower the stratus base or to maintain the fog in a sequence of events indicated above.

Some preliminary results of the tower data by Miller (1976)[22] on the flux of momentum, moisture and temperature, average inversion properties, and spectra of variables, show properties which cannot be easily explained but are basic to the understanding of the important physics related to stratus clouds, fog, and visibility. He concludes: "The intensity and depth of vertical mixing within the maritime air that is required over the extremely cold ocean water (average July temperature of 10°C) cannot be explained in terms of the usual energy sources of convection – surface heating and/or evaporation/ radiative cooling at the top of the marine layer." Subsequent results should prove significant for marine fog studies along the coast of California.

CLIMATOLOGY OF FOG NEAR SAN DIEGO

The sensors used to observe atmospheric features during the fog episodes discussed in this report are located on the coast of Southern California near San Diego and as called out in figure 1. Although fog is observed more frequently in coastal regions farther north in California, it is present sufficiently often in San Diego to ensure the use of the NELC sensors that can operate continuously and unattended during periods when fog is most likely.

[20] Miller, A, "Project Stable," *Bulletin of the American Meteorological Society*, v 56, p 52-59, 1975

[21] Goodman, JK, *The Microstructure of California Coastal Fog and Stratus*, San Jose State University, Meteorology Dept Report 75-02, October 1975

[22] Miller, A, *Wave Properties in the West Coast Inversion*, San Jose State University, Meteorology Department Report supported by the National Science Foundation, February 1976

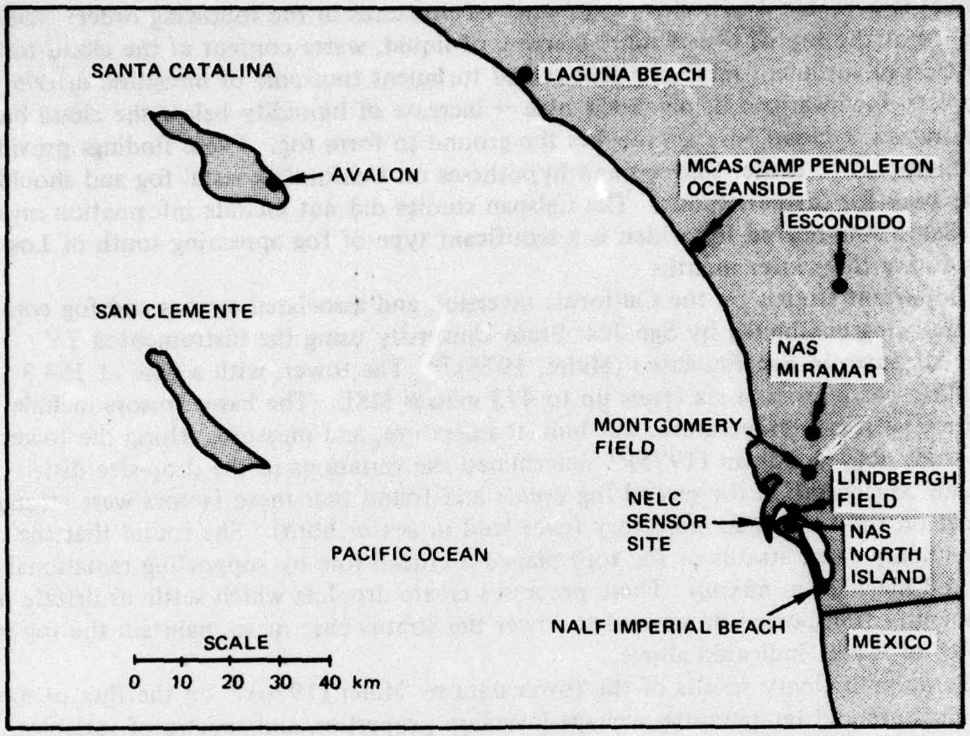

Figure 1. Map showing location of NELC sensor site.

Figure 2, data taken from records of the Naval Weather Service Facility at North Island[23] over a 22 year period, shows the number of days fog was observed with visibility less than 1 mile for the called out period. The figure shows that the least number of "fog days" occurred during the summer when the stratus related fog was predominant and the maximum number of "fog days" occurred when the Santa Ana fog was predominant. Fog is observed more often at NELC than at North Island because surface heating over the land (Pt Loma, primarily) tends to dissipate the fog as it is carried eastward from the ocean by westerly winds and because thin decks of fog are prevented from moving inland by the rapid rise in the elevation (maximum elevation about 120 m MSL) of the land immediately east of the sensor site.

Figures 3 and 4 show the percentage of time the visibility is less than 5 miles (8 km) over the ocean region off the coast of California.[23] These data are based on hundreds of ship's observations between 1946 and 1968 and show that reduced visibilities, assumed to be associated with fog, are a coastal phenomenon (Fleet Weather Facility, 1971[24]). The frequency of reduced visibilities (< 8 km) is greater in the summer than in the winter near San Diego. This seasonal difference, as shown in figures 3 and 4, appears to be opposed to the data presented in figure 2. Apparently, dense fogs with visibilities less than 1 mile (1.6 km) are more likely in the winter while light fog conditions

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[23] Fleet Weather Facility, San Diego, *Local Area Forecaster's Handbook*, March 1969

[24] Fleet Weather Facility, *Climatological Study – Southern California Operating Area*, prepared by NWSED Asheville, March 1971

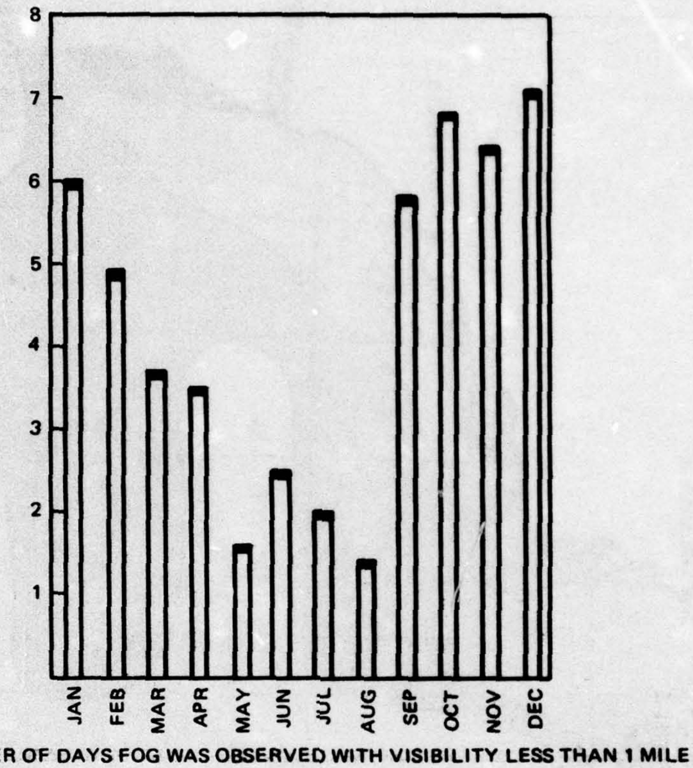

Figure 2. Distribution of fog days by month at North Island (San Diego) January 1946 through July 1968.

producing visibilities between 1 and 5 miles (1.6 and 8 km) are more likely in the summer. This indicates that visibilities between 1 and 5 miles (1.6 and 8 km) are more likely in stratus cloud related fogs than in Santa Ana-related fogs. When Santa Ana-related fogs occur visibilities are most likely to be less than 1 mile (1.6 km). These deductions agree with observations noted at the NELC sensor site.

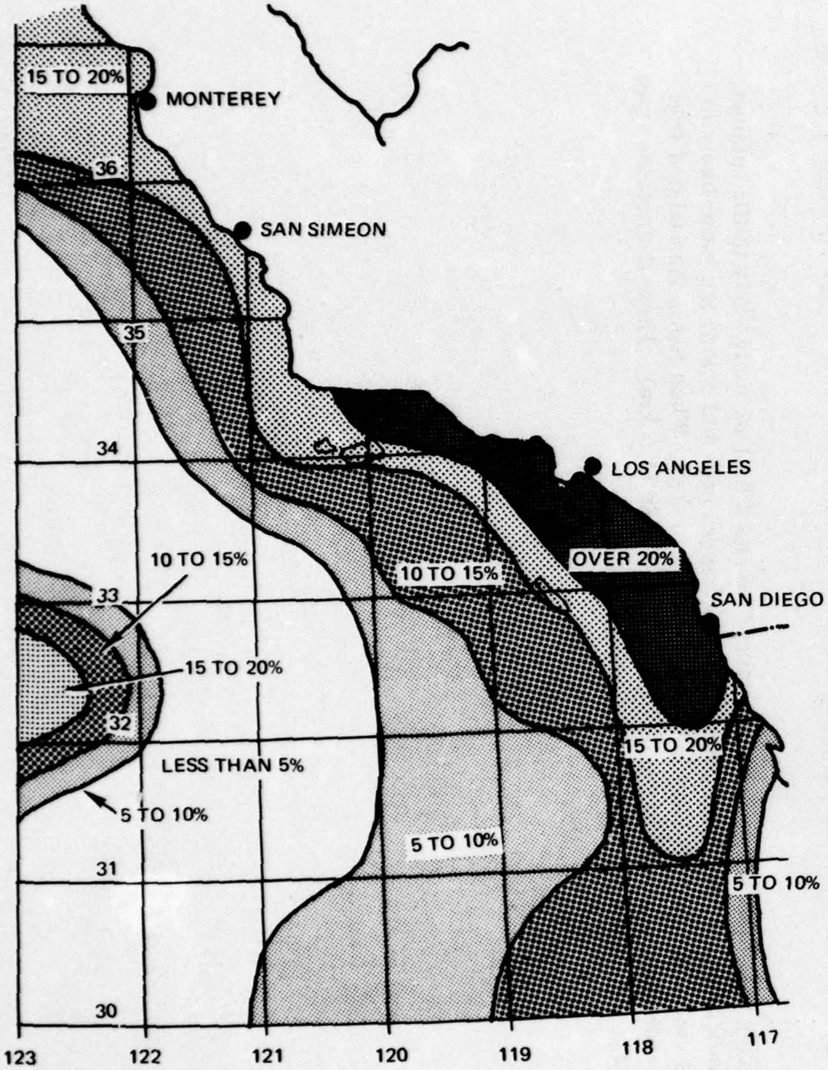

Figure 3. Spatial distribution of the percentage of time visibility is less than 5 miles (8 km) over the ocean region near San Diego during the summer months.

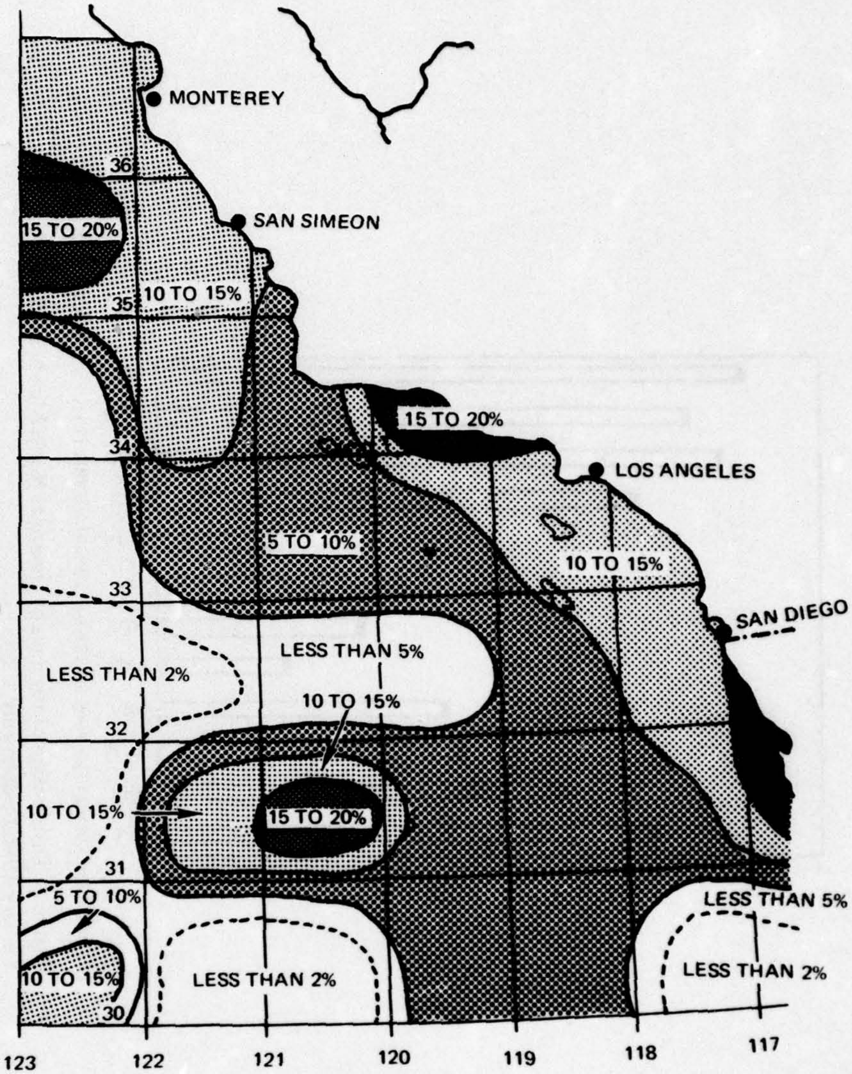

Figure 4. Spatial distribution of the percentage of time visibility is less than 5 miles (8 km) over the ocean region near San Diego during the winter months.

FOG CLIMATOLOGY OF NORTH ISLAND FOR 1975

Fog occurrences for North Island in 1975 were casually examined to determine features not made evident by normally available climatological data.

Figure 5 shows the number of days with fog (visibility ⩽ 3 mi, 4.8 km) by month for 1975 at North Island. Comparison of figure 5 to figure 2 (for visibilities ⩽ 1 mi, 1.6 km) indicates that the annual variation of fog in 1975 does not represent the long-term average. A deviation of a short-term average from the long-term average is typical of many meteorological parameters. Thus, fog forecasts, like most meteorological elements, must be given individual consideration for each synoptic situation.

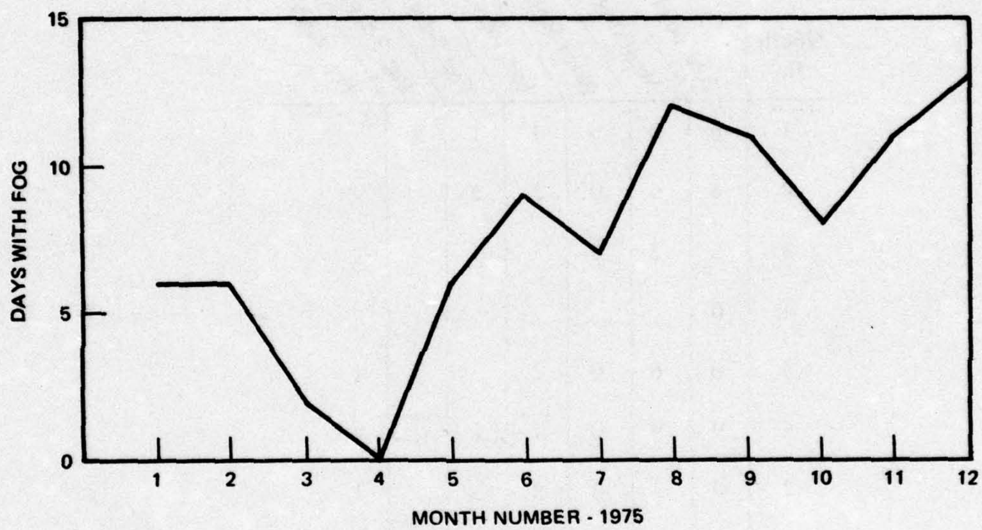

Figure 5. Distribution of the number of days with fog (visibility ⩽ 3 mi) by month at North Island (San Diego) during 1975.

Table 1 gives the distribution of fog periods by month for 1975 according to type and the number of fog episodes occurring in sequences of 2, 3, or 4 days. Sixty-two percent of the fog days occurred in sequences of up to 6 days. Apparently, synoptic conditions conducive for fog formation can prevail for several days once they are established. This tendency for fog to be repetitive is heeded by the forecasters at the Naval Weather Service Facility at North Island.

Figure 6 shows the number of days fog (visibilities ⩽ 3 mi, 4.8 km) occurred at North Island in 1975 according to the hour of the day for both fog types, Santa Ana (SA)-related fog and stratus cloud (SC)-related fog. The figure shows that fog at North Island is predominantly a nighttime phenomenon particularly for SC fog. SA fog is only slightly more likely at night. The rapid decrease in the number of days with fog after 0700 PST shows the great influence of solar heating. The steady increase in the days with SC fog after 1800 PST until 0500 PST supports a continuous cooling process during the night for SC fog. The plateau of the number of days with SA fog after 2100 PST indicates little dependence on time after sunset.

TABLE 1. DISTRIBUTION OF FOG DAYS BY MONTH, TYPE, AND SEQUENCE DAYS AT NORTH ISLAND (SAN DIEGO) DURING 1975. (FOG OCCURRENCE BETWEEN 1800 PST ONE DAY AND 0600 THE NEXT DAY.)

Month No	Total no of fog days	No of stratus fog days	No of Santa Ana fog days	Fog, 1 day only	Fog, 2-day sequence	Fog, 3-day sequence	Fog, 4-day sequence
1	6	0	6	1	1	1	
2	6	6	0	2	2		
3	2	2	0		1		
4	0						
5	6	6	0	2			1
6	9	9	0	7	1		
7	7	7	0	3			1
8	12	12	0	5		1	1
9	11	10	1	9	1		
10	8	5	3	1	1		1 (6 days)
11	11	5	6	3			2
12	13	2	11	4		3	

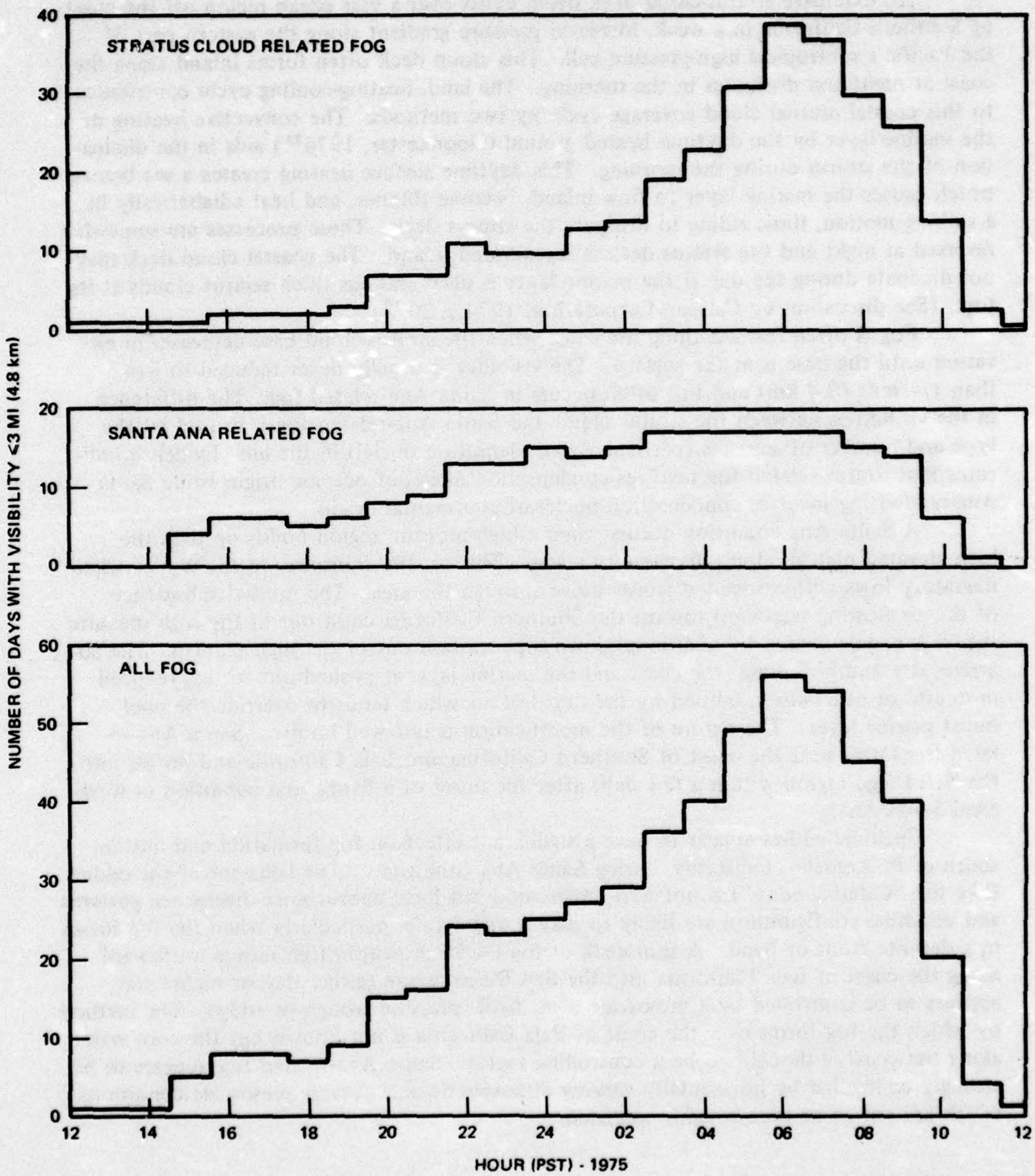

Figure 6. Distribution of the number of days with fog (visibility ≤ 3 mi) by hour at NELC during 1975 according to the type of fog.

FOG TYPES IN SOUTHERN CALIFORNIA

An extensive stratus-cloud deck often exists over a vast ocean region off the coast of Southern California in a weak, low-level pressure gradient along the eastern part of the Pacific's subtropical high-pressure cell. This cloud deck often forms inland along the coast at night and dissipates in the morning. The land, heating-cooling cycle contributes to this coastal diurnal cloud coverage cycle by two methods. The convective heating of the marine layer by the daytime heated ground (Noonkester, 1974[25]) aids in the dissipation of the stratus during the morning. This daytime surface heating creates a sea breeze which causes the marine layer to flow inland, become thinner, and heat adiabatically by a sinking motion, thus, aiding to dissipate the stratus deck. These processes are somewhat reversed at night and the stratus deck is regenerated inland. The coastal cloud deck may not dissipate during the day if the marine layer is deep and has thick stratus clouds at its top. (See discussion by Calspan Corporation, 1974 p 20.[19])

Fog is often formed along the coast when the stratus-cloud base decreases in elevation until the base is at the surface. The visibility is usually never reduced to less than 1/4 mile (0.4 km) and this often occurs in Santa Ana-related fog. The difference in the visibilities between the stratus cloud and Santa Ana-related fog is caused by the type and number of aerosols (particularly condensation nuclei) in the air. Evidence indicates that stratus-related fog involves condensation nuclei of oceanic origin while Santa Ana-related fog involves condensation nuclei of continental origin.

A Santa Ana condition occurs when a high-pressure region builds up over the high elevated plateau along the western states. This usually transpires in the winter when migratory lows with associated fronts move through the area. The normal subsidence of the air flowing westward toward the Southern California coast out of the high-pressure region is supplemented by additional downslope motion out of the high plateau. The air arrives dry and hot along the coast and the marine layer is pushed out to sea, reduced in depth, or otherwise modified by the dry, hot air which tends to override the cool moist marine layer. The nature of the modification is not well known. Santa Ana-related fog forms near the coast of Southern California and Baja California and moves into the San Diego region within a few days after the onset of a Santa Ana condition (a weakened Santa Ana).

Cyclonic eddies appear to have a significant effect on fog formation and motion south of Pt Arguello, California, during Santa Ana conditions. The behavior of the eddies (like the "Catalina eddy") is not well understood but local convergence-divergence patterns and coastline configuration are likely to play a major role, particularly when the fog forms in a definite front or band. A thin deck of fog (< 30 m deep) often moves northward along the coast of Baja California into the San Diego region (either day or night) and appears to be controlled by a mesoscale wind field (pressure trough or eddy). The method by which the fog forms over the coast of Baja California is not known but the cool water along the coast is thought to be a controlling factor. Santa Ana-related fog appears to be strongly controlled by horizontally varying atmospheric and oceanic mesoscale conditions which are yet to be even roughly modeled.

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[25] Naval Electronics Laboratory Center Technical Report 1919, *Convective Activity Observed by FM-CW Radar*, by VR Noonkester, 10 May 1974

Although stratus-related fog exhibits considerable horizontal variability, a horizontally independent model has emerged which appears to have considerable merit. Figure 7 shows a sequence of processes (outlined in the section BACKGROUND) considered to lead to fog formation beneath a stratus base. Considerable data have shown that the cloud top must be below about 400 metres before the cloud base *will* lower to form fog. Apparently this process cannot maintain a saturated condition in a layer greater than about 400 metres.

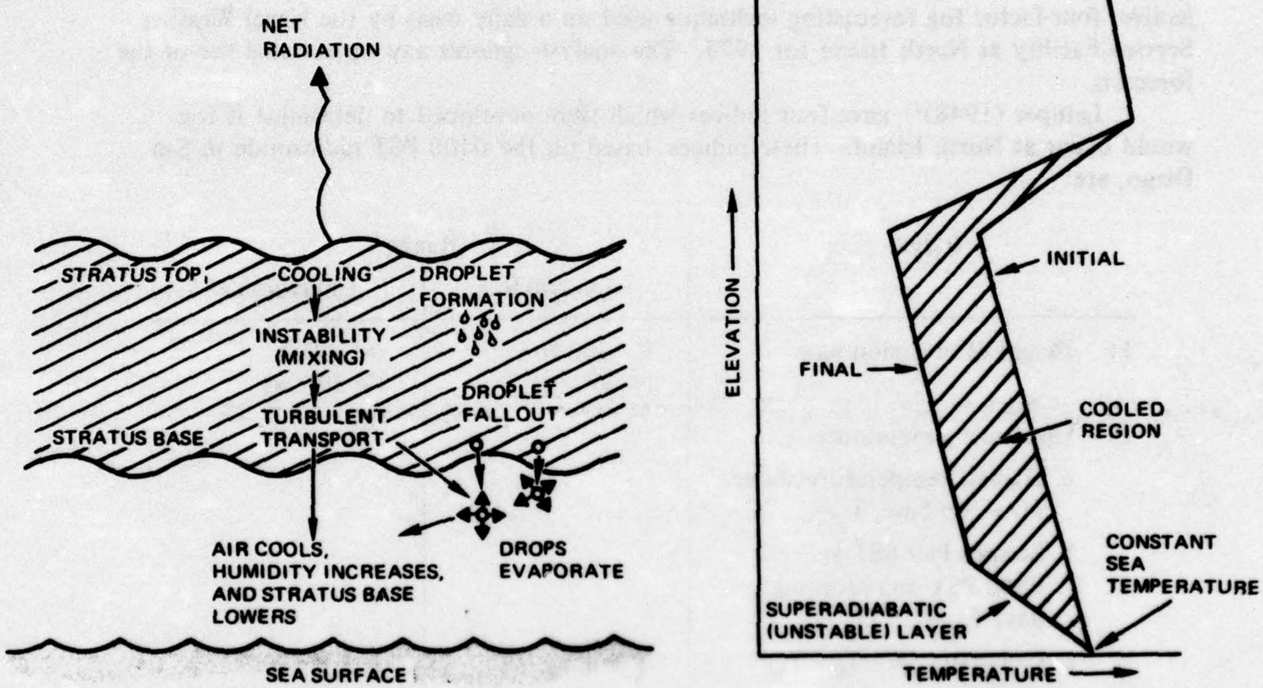

Figure 7. Sequence of processes considered to be creating fog and low-level cooling during the presence of stratus clouds over Southern California.

The sequence of events in the qualitative model, as given, is independent of sea-surface temperature and does not suggest potentially important factors like mesoscale divergence patterns or wind shear turbulence effects, but observations (eg, Calspan Corporation, 1974[19]) support the basic features of the model. An apparent consequence of *continual operation* of the processes would be the creation of a surface-based superadiabatic layer over the water. Data from several sources indicate that such an unstable layer is often present and are discussed in the section MARINE LAYER STRUCTURE.

FOG FORECASTS AT NORTH ISLAND, SAN DIEGO, CALIFORNIA

The adequacy, reliability, or success of environmental forecasts is difficult to evaluate. One practical method would be to determine the loss of lives, money, operational effectiveness, and material due to an inadequate forecast but this would be exceedingly difficult. Wheeler (1974)[1] gave details on losses associated with fog but did not indicate if a fog forecast was sought or obtained, and if one was obtained, was it heeded or was it partially or wholly inadequate. Because a forecast can be adequate for one purpose and inadequate for another, an evaluation of a fog forecasting technique may result in several measures of merit. This section will discuss a simple reliability analysis of an objective, four-factor fog forecasting technique used on a daily basis by the Naval Weather Service Facility at North Island for 1975. The analysis ignores any operational use of the forecasts.

Leipper (1948)[11] gave four indices which were developed to determine if fog would occur at North Island. These indices, based on the 0400 PST radiosonde in San Diego, are:

Index	Range: Favorable	Range: Unfavorable
1) Height of inversion base	≤ 1300 ft (≤ 397 m)	≥1300 ft (≥ 397 m)
2) Upper-air temperature		
a. Highest temperature above inversion base, T_a =___°C		
b. Scripps Pier SST at 0800 PST on preceding day, T_w =___°C		
c. Calculate: $X = T_a - T_w$	$X \geqslant 0°C$	$X < 0°C$
3) Surface moisture index		
a. Dew point for North Island at 1630 PST on preceding day, T_c =___°C		
b. Calculate: $Y = T_c - T_w$	$Y \geqslant -5°C$	$Y < -5°C$
4) Radiation index		
Mixing ratio w at 10 000 ft (3050 m)	$w \leqslant 3.5$ gm/kgm	$w > 3.5$ gm/kgm

If all four indices are favorable fog is expected to occur between 1800 PST that evening and 0600 PST the following morning at North Island. A forecaster may make a fog forecast opposed to the indices (favorable or unfavorable for fog) if he considers the synoptic conditions to be changing appropriately. The analysis of the fog forecast was made based entirely on the indices and surface observations at North Island. Fog was considered to be present at North Island if the visibility was ≤ 3 miles (4.8 km) and fog was given as the

reason for the restriction at any time between 1800 PST and 0600 PST. Detailed fog forecasts made by North Island forecasters concerning specifics of time of occurrence and visibilities were not considered in this analysis.

Table 2 contains a breakdown of the success of the fog indices for stratus cloud (SC) or Santa Ana (SA)-related fog. Frontal and radiation fog were not considered in this analysis. The associated meteorological conditions, prior to SC-or SA-type fog, were determined from North Island surface observations. The presence of stratus and the apparent lowering of the stratus base were used as criteria for identifying SC conditions. SA conditions were identified by low humidities, clear skies, and synoptic pressure pattern.

TABLE 2. SUCCESS OF FOG FORECASTS BY CATEGORY AT NORTH ISLAND (SAN DIEGO) DURING 1975. (FOG OCCURRENCE BETWEEN 1800 PST ONE DAY AND 0600 PST THE NEXT DAY.)

Fog Type Observed for Forecast	All Indices Favorable				One or More Indices Unfavorable			
	Fog Forecast		No Fog Forecast		Fog Forecast		No Fog Forecast	
	Fog Observed?				Fog Observed?			
	Yes	No	Yes	No	Yes	No	Yes	No
All cases	28	15	1	8*	21	11	17	136*
Stratus-type fog	20	7	1	2*	10	5	13	–
Santa Ana-type fog	8	8	0	6*	11	6	4	–

Number of fog forecast periods (1 per day):	237
Number of fog periods with fog:	67
Percent of forecast periods with fog:	28
Number of fog conducive periods (see text):	93
*Number of periods not considered conducive for fog:	144
Number of periods fog forecast was successful for fog conducive periods:	49

If all forecast days (237 days – table 2) were forecast to have <u>no</u> fog, then the success of this "safe" forecast would be (1-67/237) X 100 or 72 percent. This high success rate might suggest that attempts to improve fog forecasts could not increase the forecast success rate appreciably. This is misleading because there are many days which essentially do not have meteorological conditions favorable for fog that can be easily identified. A realistic evaluation of fog forecasts should only consider those days (or fog forecast periods) conducive for fog. These are days where a forecaster's skill is challenged. For the purpose of this analysis a fog conducive day is defined as a day when fog is observed (hindsight) or forecast to occur. The method by which fog conducive days are selected is crucial in the test on the success rate of fog forecasting. The days selected (by the definition) are intended to represent days which the majority of forecasters experienced in fog forecasting at North Island would prudently select, and which must be considered as potential fog days. Both the guidance of the indices plus the skill of the forecasters in accepting or rejecting the indices are tested on fog conducive days. There

are 93 fog conducive days.* If all fog conducive days are forecast to have no fog, the forecast success rate is (1-67/93) X 100 or 28 percent. Reliable fog forecasts on fog conducive days could obviously make an improvement in the success rate. There were 49 successful fog forecasts made on fog conducive days. The success rate of these forecasts is (49/93) X 100 or 53 percent. Thus, the combined guidance of the indices and subjective talents of the forecasters have increased the success rate by 25 percent above a "no-fog" forecast. A success rate of 53 percent is still too low to be considered more than a "guess" or "chance" forecast. A success rate near 75 percent is sometimes considered to be the success rate of general meteorological forecasts. Methods should be developed to increase the success rate of the fog forecasts from 53 percent to approximately 75 percent.

The success rate of fog forecasting can be evaluated for the categories "indices favorable" and "indices unfavorable" as shown in table 3. When all indices were favorable, the success rate was 56 percent for all fog days, 70 percent for SC days, and 36 percent for SA days. The success rate for SC fog days is comparable to the general meteorological success rate (~75%) while the success rate for SA fog days is low. When the forecasters decided to forecast contrary to the indices, the success rate was 89 percent for all forecast days. The combined success rate within the category of all "indices favorable" was 69 percent for all fog days, 73 percent for SC days, and 64 percent for SA days. Forecasting improvement is particularly needed during SA conditions when all indices are favorable for fog.

TABLE 3. EVALUATION OF FOG FORECASTING AT NORTH ISLAND (SAN DIEGO) FOR 1975 USING FOG INDICES AS A GUIDE.

	Indices Favorable for Fog						Indices Unfavorable for Fog					
Fog Category	No Days Indices Favorable	No Days Indices Succeeded	Success of Indices (%)	No Days Indices Not Accepted	Success on Change (%)	Total Success (%)	No Days Indices Unfavorable	No Days Indices Succeeded	Success of Indices (%)	No Days Indices Not Accepted	Success on Change (%)	Total Success (%)
All fog days	52	29	56	9	89	69	185	147	79	32	66	85
Stratus fog days	30	21	70	3	67	73	–	–	–	15	67	–
Santa Ana fog days	22	8	36	6	100	64	–	–	–	17	65	–

When one or more indices were unfavorable, the success rate was 79 percent for the indices alone. Upon changing the forecast indicated by the indices, the forecaster was successful 66 percent of the time (32 days). Thus, the overall success rate was 85 percent. A high success rate was expected in this situation because most days can be easily

*There were 18 days when fog was observed but not forecast, 26 days when fog was forecast but not observed, and 49 days when fog was both forecast and observed.

identified as poor candidates for fog and the indices would often indicate unfavorable fog conditions. The success rate would be 79 percent if no fog were forecast for all the days when the indices were unfavorable. The SC or SA categories were not identified under the no-fog forecast because neither fog condition could be easily identified.

In general, the overall capability of fog forecasts (for visibilities ⩽ 3 mi, 4.8 km) at North Island needs improvement (53%) when both the indices and the forecaster's skills are considered on fog conducive days. When all indices were favorable, changes by the forecaster made definite improvements (56% to 69% for all fog cases) although the small number of changes reduces confidence in this conclusion. When the indices were unfavorable, changes by the forecaster improved the success rate appreciably. The success rate for SC conditions was at a reasonably high level (73%) when all indices were favorable; this might not be expected because the indices were developed for SA conditions.

A similar analysis could be completed for fog having a visibility maximum of less than 3 miles (4.8 km). The resulting success rate is likely to be considerably less for other visibility maxima (eg, < 1 mi) when local naval operations are likely to be more severely affected.

A fog forecast reliability analysis should include details on the forecast and observed fog onset time, duration, and specifics on the visibility; however, this would be difficult to accomplish.

An analysis is being completed on the values of the indices used to make the forecasts (237 days – table 2) to determine (a) how best to make use of trends in the indices, (b) which indices are the most important, and (c) whether the critical values of the indices (favorable or unfavorable category) should be changed. These results will be published in another report.

The major factor for consideration in this analysis is the relatively low overall success rate (53%) of fog forecasting for North Island. This is clearly not a weakness of the forecasters because they made an excellent attempt to utilize the only objective technique available. The four-factor objective technique appears to be a good forecast guide relative to most objective meteorological aids. Improvements in the objective technique might be expected using mesoscale-dependent parameters and continuous assessments of atmospheric conditions. Use of the 1600 PST radiosonde at Montgomery Field, San Diego, California, to make a short-range fog forecast (commencing 2 hours later) should increase the forecast success rate.

METHOD OF STUDY

The objective of the observational program of this project was to observe many fog episodes representing conditions throughout the year at San Diego. The primary atmospheric information was obtained by the sensors at the NELC sensor site. A fog episode is considered to be the sequence of events prior to, during, and after fog has occurred. For this purpose, fog is considered to be present at the sensor site when the visibility measurements are indicated to be below about 1 mile at least part of the time during periods when visibility is reduced by water droplets. Measurements of fog episodes for a period of at least a year were desired because the processes of fog formation and dissipation vary during a year according to the annual change in the synoptic patterns of meteorological and oceanographic parameters.

An attempt to maximize the probability of observing fog episodes by the sensors was made by making sensor observations during numerous conditions conducive to fog. These conditions were determined partly by the synoptic pattern and by the fog forecast made at the Naval Weather Service Facility at North Island. Observation periods extended from 1 day to over a month. Many fog episodes representing a large number of synoptic conditions have been experienced since commencing the study in 1974. Table 4 gives the fog measurement periods considered in this report.

TABLE 4. FOG MEASUREMENT PERIODS COVERED.

From	To
1974	
14 Jan	5 Feb
27 Feb	28 May
6 June	23 July
13 Oct	22 Oct
4 Nov	19 Nov
26 Nov	29 Nov
10 Dec	28 Dec
1975	
3 Jan	9 Jan
15 Jan	21 Jan
1 May	23 May
10 June	2 July
20 Oct	24 Oct
3 Nov	5 Nov
12 Nov	17 Nov
26 Nov	28 Nov
3 Dec	5 Dec
17 Dec	19 Dec

SENSORS AND SUPPORTING DATA

Measurements of atmospheric features have been made during fog episodes using various combinations of the following sensors at the coastal site:

- FM-CW radar
- Acoustic echosounder
- Visiometer (MRI Model 1580A)
- Transmissometer (AN/GMQ 10C)
- Ceilometer (AN/GMQ 13C)

- Lidar
- Radiosondes
- Surface measurements of pressure, temperature, relative humidity, and wind

The characteristics of these sensors are given in several reports: Richter, 1969,[26] Richter et al, 1972,[27] and Richter et al, 1976.[28]

The primary sensors of the vertical atmospheric structure are the FM-CW radar and the acoustic echosounder. The radar receives backscatter energy from regions where the radio refractive index is varying (primarily moisture controlled) due to turbulent mixing processes along a radio refractive index gradient. The predominant echoes observed by the radar at the coastal site include returns from the top of the marine layer where waves (stable and unstable) are often present, from forced and free convection near the surface, from rain or drizzle and from insects. These echoes are usually observed below 1 kilometre. The acoustic echosounder receives backscatter energy from regions where the acoustic refractive index is varying (primarily temperature controlled) due to turbulent mixing processes along an acoustic refractive index gradient. The radar and echosounder usually receive echos from the same regions because temperature and moisture mixing usually occur in the same region; however, exceptions which may be significant have been found (fig 33). The range resolution of the radar was usually 2 metres and the range resolution of the echosounder was usually either 2 or 34 metres.

The ceilometer and lidar (Noonkester, et al, 1974[29]) receive optical radiation scattered from particulates in the atmosphere up to several kilometres. The lidar receives backscatter energy while the ceilometer receives sidescatter energy. Suspended water droplets are usually the major scattering particles. These sensors are used primarily to detect the elevation of clouds; they can observe the lowering of a cloud base to the ground during fog formation and can detect some fog structure.

The scattered energy observed by the radar, echosounder, lidar, and ceilometer are recorded by filming the signal on an intensity modulated oscilloscope using a 35 mm shutterless camera. The film shows a continuous picture of the relative echo intensity as a function of elevation and time for the medium carried through the atmospheric volume probed by the sensor.

The visiometer and transmissometer measure the visibility over short and long paths, respectively. Both instruments sense the optical effects of suspended particles which also affect the lidar and ceilometer. Again water droplets usually create the greatest variability in the measured visibility. The visiometer and transmissometer have a greater resolution in the low visibility range and their output is recorded by analogue techniques.

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[26] Richter, JH, "High Resolution Tropospheric Radar Sounding," *Radio Science,* v 4, p 1261-1268, 1969

[27] Richter, JH, DR Jensen, and ML Phares, "Scanning FM-CW Radar Sounder," *The Reviews of Scientific Instruments,* v 43, p 1623-1625, 1972

[28] Richter, JH, DR Jensen, and VR Noonkester, *A Coastal Multisensor Measurement Facility at San Diego,* Conference on Coastal Meteorology (preprints), American Meteorological Society, Boston, MA, Sept 1976

[29] Noonkester, VR, DR Jensen, JH Richter, W Viezee, and RTH Collis, "Concurrent FM-CW Radar and Lidar Observations of the Boundary Layer," *Journal of Applied Meteorology,* v 13, p 249-256, 1974

Radiosondes can be obtained with (1680 MHz) or without (403 MHz) winds at the sensor site. The rise rates of the radiosonde package are usually made to be slow and the transmitted output is often made to provide more humidity than temperature by simple rewiring of the radiosonde.

The surface dry and wet bulb temperatures are obtained from wet and dry thermistor beads placed about 44 metres MSL. The pressure is measured by a sensitive electronic device labeled "vibrotron" (Richter and Gossard, 1970[30]) and is at 35 metres MSL. The wind direction and speed are measured by a UMQ5 aerovane placed at 55 metres MSL. The measurements by these sensors are recorded on a multichannel Speedomax recorder.

Standard meteorological surface observations are obtained from the Naval Weather Service Facility at North Island for each fog episode observed by the sensors. Surface observations were sometimes obtained from local stations making regular or intermittent standard observations. These stations include (fig 1): Lindbergh International Airport, NAS Miramar, NALF Imperial Beach, MCAS Camp Pendleton, and San Clemente Island. Other surface observations are obtained from a larger area in Southern California for selected times when mesoscale analyses are completed. Regular radiosonde data are obtained from the National Oceanographic and Atmospheric Administration (NOAA) weather station at Montgomery Field (fig 1). Selected maps are received from the NOAA National Weather Central by facsimile recorder to determine the synoptic weather patterns during fog episodes.

[30]Naval Electronics Laboratory Center Technical Report 1718, *Lower Tropospheric Structure as Seen by a High-Resolution Radar*, by JH Richter and EE Gossard, 26 June 1970

SANTA ANA-RELATED FOG

Many fog episodes related to Santa Ana conditions have been observed by the coastal sensor system. Santa Ana-related fog has been observed to occur in spatially distributed forms which appear to vary around two primary types. One type appears as a thick (~200-m) layer which moves onto the coast sometimes like a front from the west. The other type appears as a thin (~50-m) layer which moves northward along the coast up from Baja California. This section discusses Santa Ana-related fog episodes which have the two primary forms and other episodes which have intermediary forms.

OBSERVATIONS DURING DECEMBER 1974

13 AND 14 DECEMBER

Santa Ana conditions prevailed for many days during December 1974 and numerous fog episodes occurred. At 1500 PST on 13 December, a fog bank moved past the sensor site after it was observed for several hours offshore. The leading portion of the fog bank had a distinct straight edge extending in a general north-south direction and had a rolling, turbulent motion. The fog bank had the appearance of an "American haboob" (Idso, et al, 1972), [35] a relatively fast-moving dust bank produced by the outflow of cold air from desert thunderstorms.

The visibility, given in figure 8, decreased rapidly from near 4 mi (6.4 km) to 0.15 mi (0.24 km) as the fog front passed the sensors. The fog-frontal passage was accompanied by a wind shift of 40° from the northwest to north, a temperature decrease of 3°C, a humidity increase of 15 percent, and a weak, but definite pressure trough as shown in figure 9. These wind, temperature, and pressure changes are characteristic of synoptic-scale cold-frontal passages.

The synoptic sea-level pressure map, shown in figure 10, does not reveal any circulation feature which would produce the surface observations at the sensor site during the fog-frontal passage. Mesoscale circulation features were apparently controlling the fog-front formation and motion. A detailed mesoscale analysis of hourly surface weather observations made at many locations in the Southern California region was completed starting many hours before the fog-frontal passage. These analyses were difficult because some mountain pressures did not appear reasonable, the surface winds often appeared to be unrelated to the pressure gradient, and no data were taken from over the open ocean.

Figures 11 and 12 show the resulting mesoscale analysis of the sea-level pressure at 1200 and 1500 PST, respectively, on 13 December. An eddy is well developed near San Nicolas Island, while a weak pressure gradient is present over the coast. The pressure pattern in figure 11 suggests that a region of confluence (likely frontogensis region) might be present over the ocean between the coast and San Clemente Island at 1200 PST. The mesoscale analysis for 1500 PST (figure 12) indicates that the winds became more westerly east of San Diego. This change would tend to weaken the region of confluence. If present, a frontal zone would be moved toward the coast.

Air-parcel trajectories were graphically constructed to estimate the source of air arriving near San Diego around 1500 PST. Figure 13 shows two possible trajectories. The trajectory starting near Santa Barbara was a downstream (forward in time) trajectory and the other one was an upwind (backward in time) trajectory. These trajectories

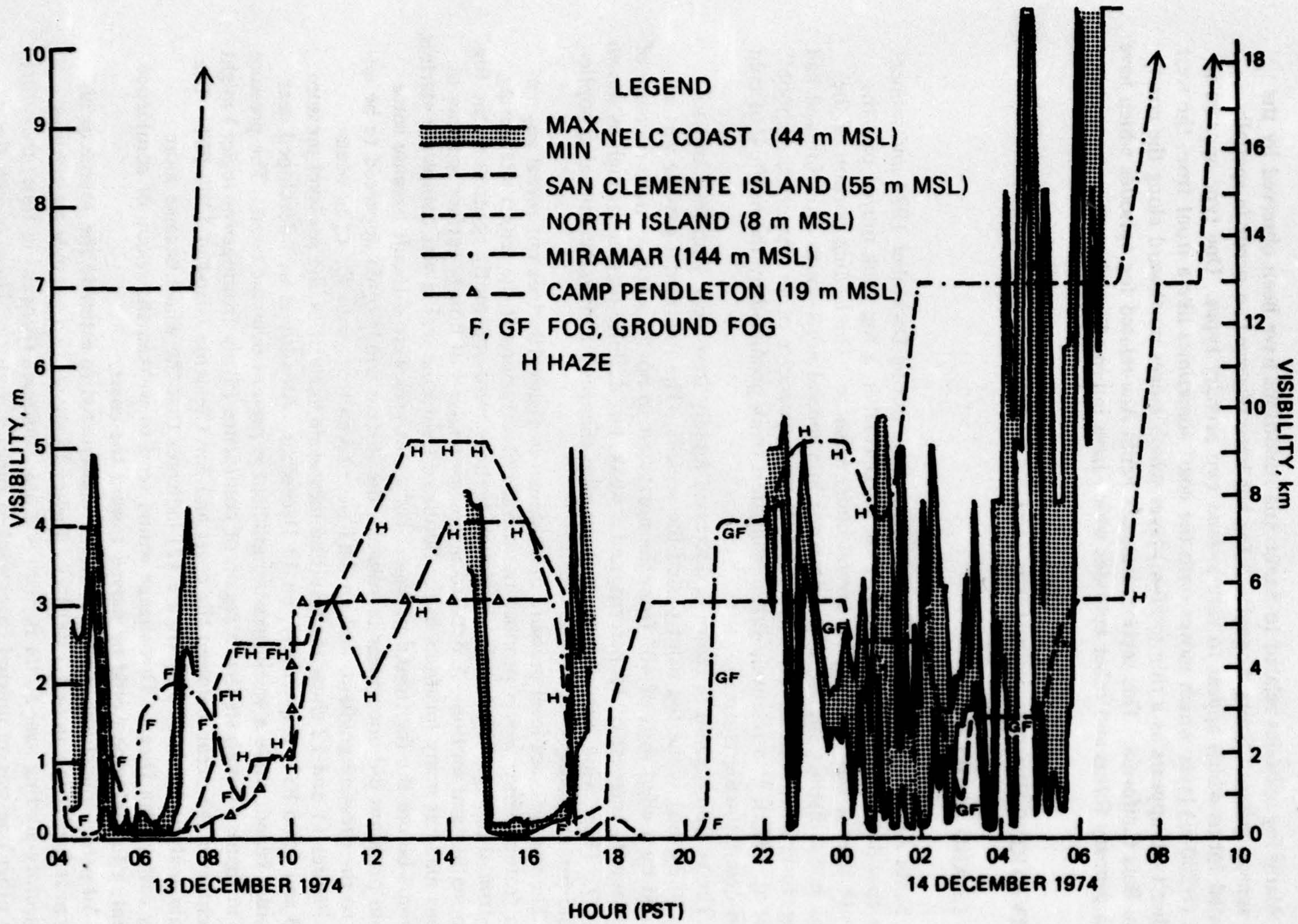

Figure 8. Visibility reported at five sites during fog events on 13 and 14 December 1974.

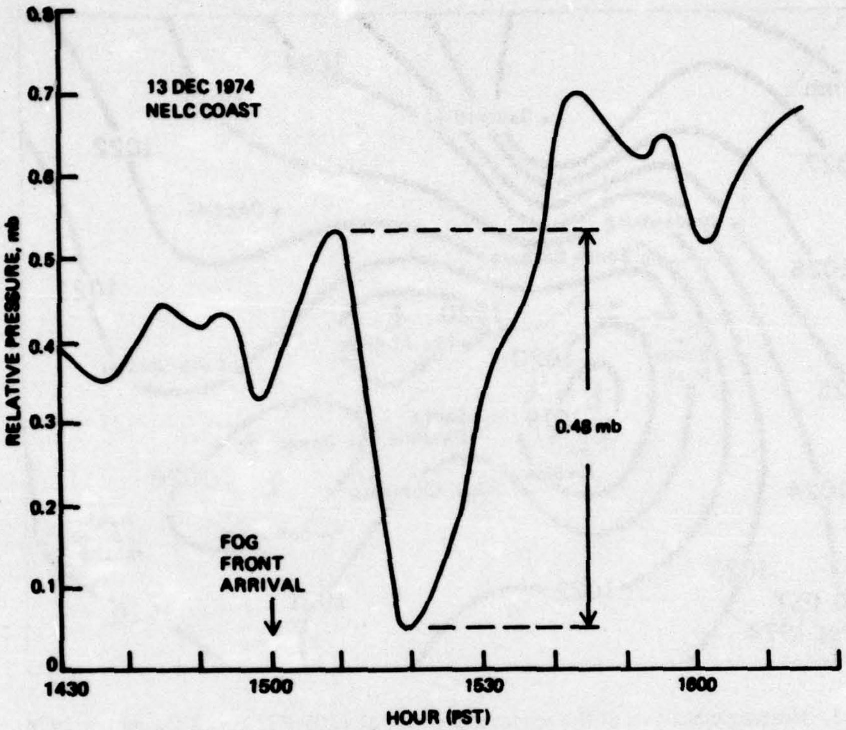

Figure 9. Pressure change following a sudden onset of fog on 13 December 1974.

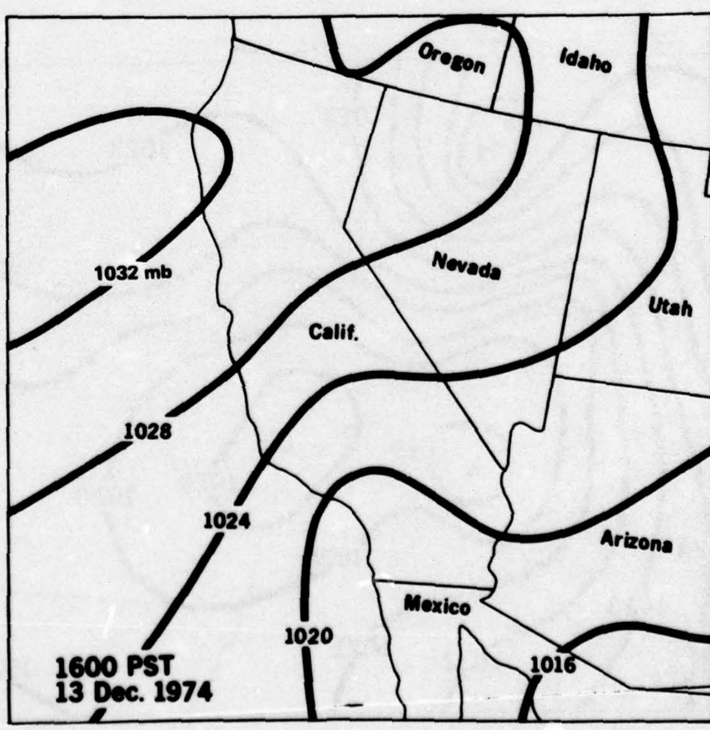

Figure 10. Synoptic sea-level pressure map at 1600 PST on 13 December 1974.

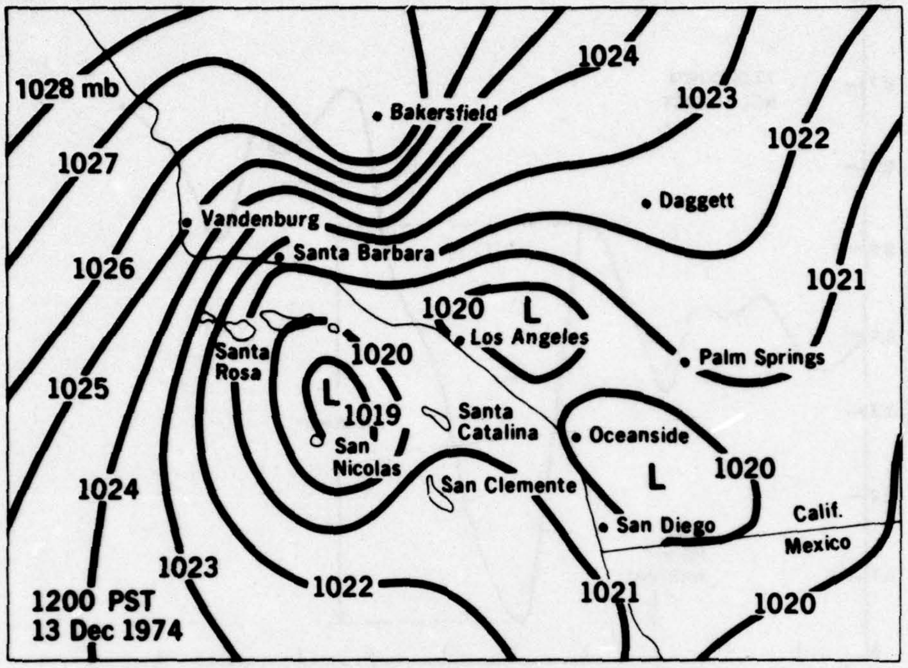

Figure 11. Mesoscale analysis of the sea-level pressure at 1200 PST on 13 December 1974.

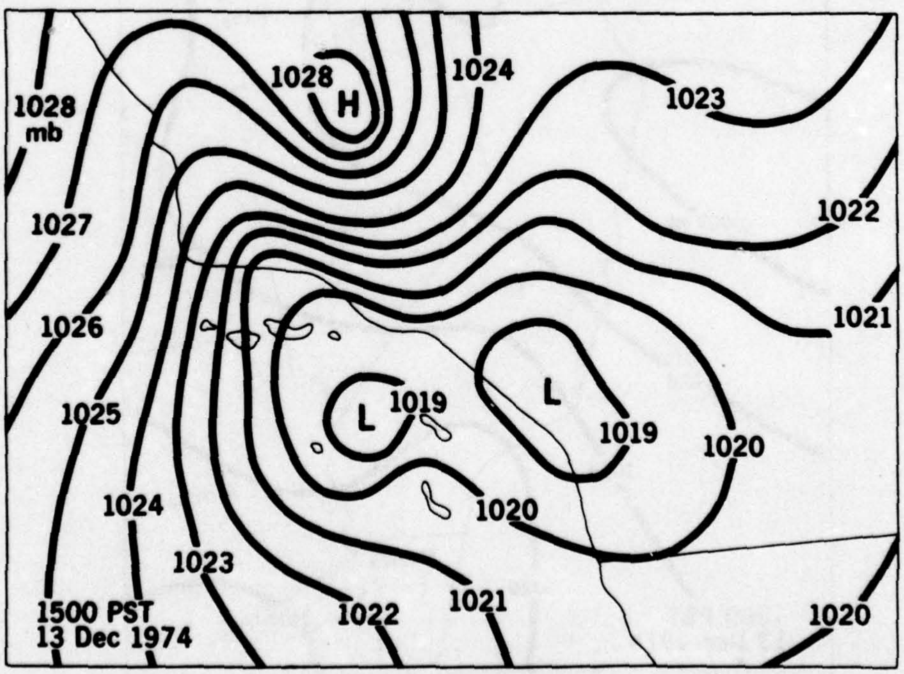

Figure 12. Mesoscale analysis of the sea-level pressure at 1500 PST on 13 December 1974.

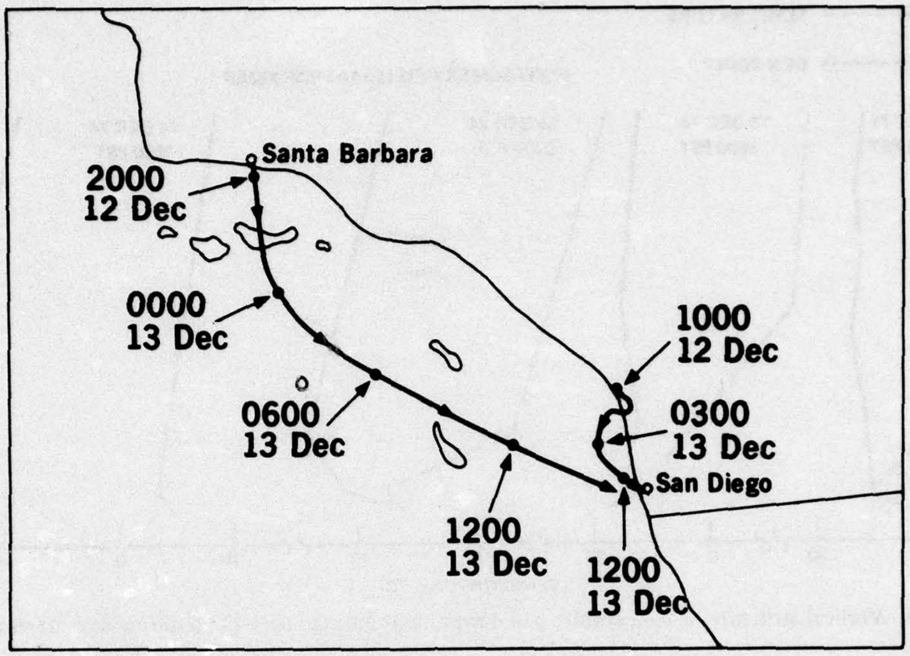

Figure 13. Air-parcel trajectory analysis for air arriving in San Diego near the time of a sudden onset of fog at 1500 PST on 13 December 1974.

indicate that the air arriving near San Diego at 1500 PST could have originated either from near Santa Barbara or Oceanside. We suggest that the air ahead of the fog front had a source north of San Diego with a short overwater trajectory while the air behind the front had a source near Santa Barbara with a long overwater path. The interaction between the mesoscale circulation in the region of confluence and the ocean temperature structure must have been favorable for the formation of fog in the air from near Santa Barbara. The air was clearly of continental origin, having continental aerosols which would be expected for the low visibilities observed. Drop-size measurements of the aerosols in this fog indicated that the aerosols had the distribution characteristic of a continental source (Desert Research Institute, private communication).

Figure 8 shows that the visibility was low at NELC during this fog event until about 1700 PST when it began to increase. The fog front did not arrive at North Island and Miramar (see figure 1) until 1700 PST; the fog prevailed 1 hr at North Island and 3 hr at Miramar. Subtle surface or terrain and circulation features appear to have controlled the fog motion in the San Diego region after the fog moved onshore.

Fog was observed at NELC between 0500 and 0700 PST on 13 December, and intermittently between 2245 on 13 December and 0545 on 14 December, as shown in figure 8. These two events did not have the frontal characteristics. Considerable variability in the visibility at sites near San Diego also occurred during these two fog events, as was observed in the late afternoon of 13 December when the distinct fog front moved past NELC.

The visibilities at San Clemente Island were 7 mi (11.2 km) or greater during these three fog episodes. This indicates that the fog was primarily a coastal event, probably associated with mesocale and sea-surface conditions.

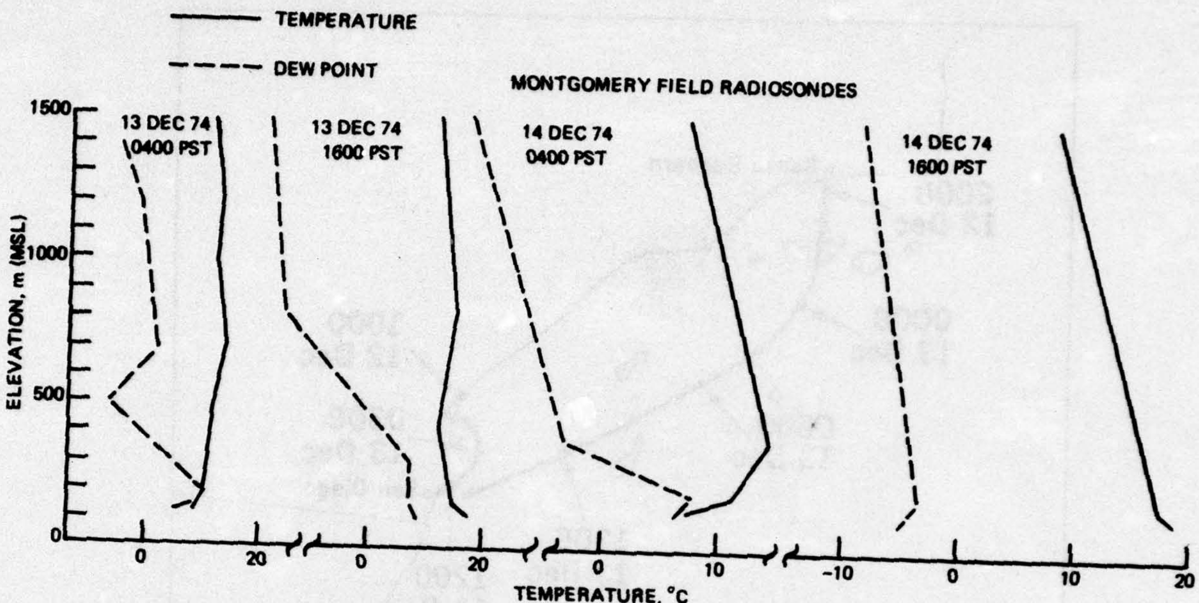

Figure 14. Vertical structure of temperature and dewpoint at Montgomery Field during days having fog.

Figure 14 shows the vertical temperature and dewpoint profiles at Montgomery Field taken near these three fog events. The depth of the marine layer is difficult to determine from these profiles. This contrasts with the profiles taken during stratus cloud-related fog conditions when the marine layer depth is clearly indicated. The 1600 PST profile taken on 13 December shows a "dry" marine layer up to 420 m. Apparently the fog bank had not advected to Montgomery Field by 1600 PST because the dewpoint was low and because the fog did not advect to Miramar until 1700 PST (see figure 1).

Fog was apparently present at Montgomery Field at 0400 PST on 13 December because saturation was indicated in the dewpoint profile between 150 and 200 m MSL (above mean sea level). The temperature profile did not suggest an inversion indicative of the marine layer top. A Santa Ana condition was clearly present at Montgomery Field at 1600 PST on 14 December after the third fog episode shown in figure 8 because the air was exceptionally dry.

Figures 15 through 19 show the sensor observations during the three fog events on 13 and 14 December 1974. The visiometer and lidar record distinctly reveals the presence of fog. The visibility had considerably less variability during the first two fog events compared to the third event. The lidar returns are strong during the period of low visibility.

The echos of the radars are exceptionally variable compared to the radar echoes observed during fog periods related to stratus clouds, when strong echoes are observed from the top of the marine layer. There appears to be some temporal continuity in radar returns near 400 m in figure 15; near 600 m until 1540 PST and near 400 m after 1600 in figure 16; and near 180 m in figure 18. Echo continuity cannot be discerned in figures 17 and 19. This indicates the absence of a well defined marine layer during these fog events.

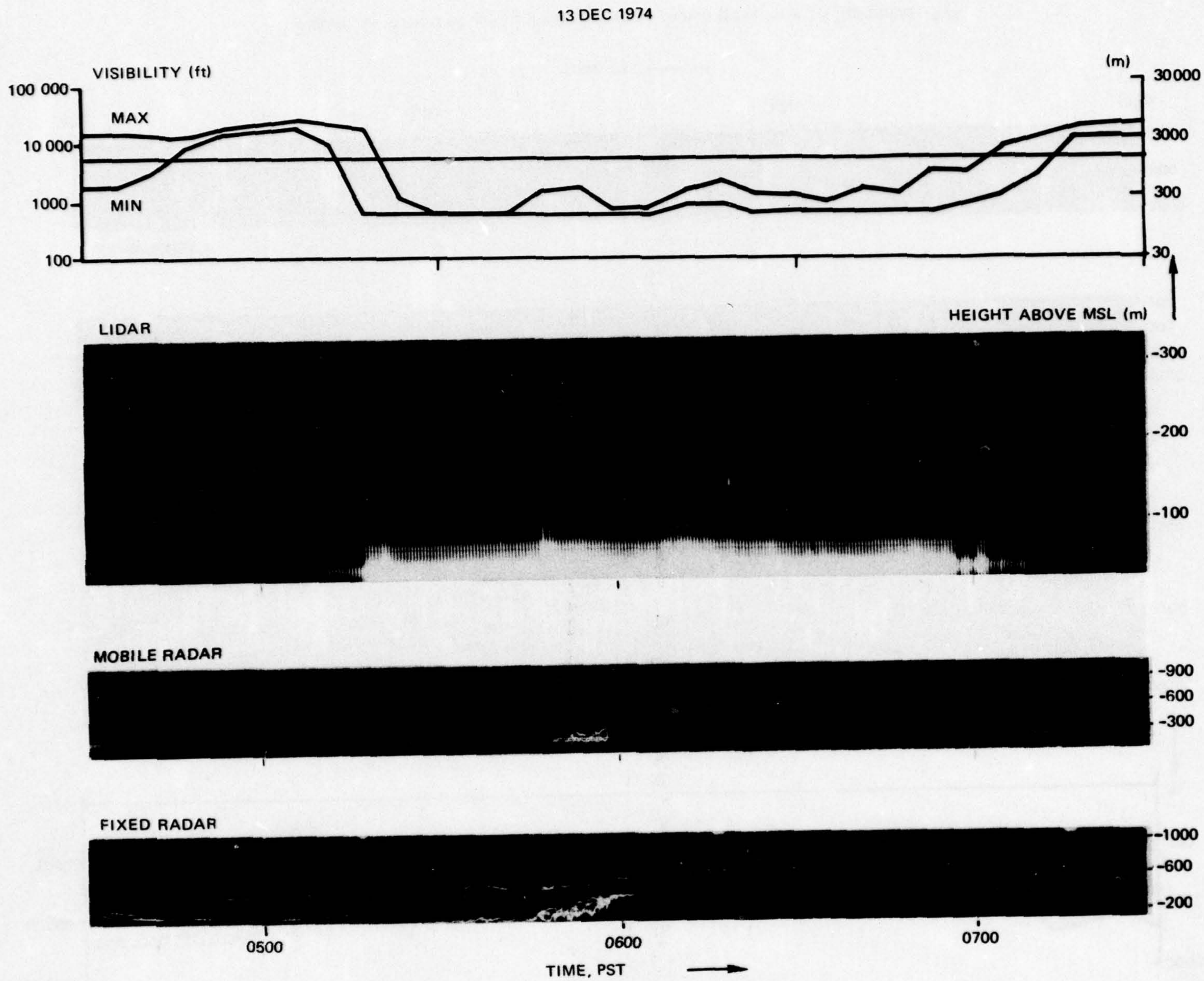

Figure 15. Sensor observations during a morning fog event on 13 December 1974.

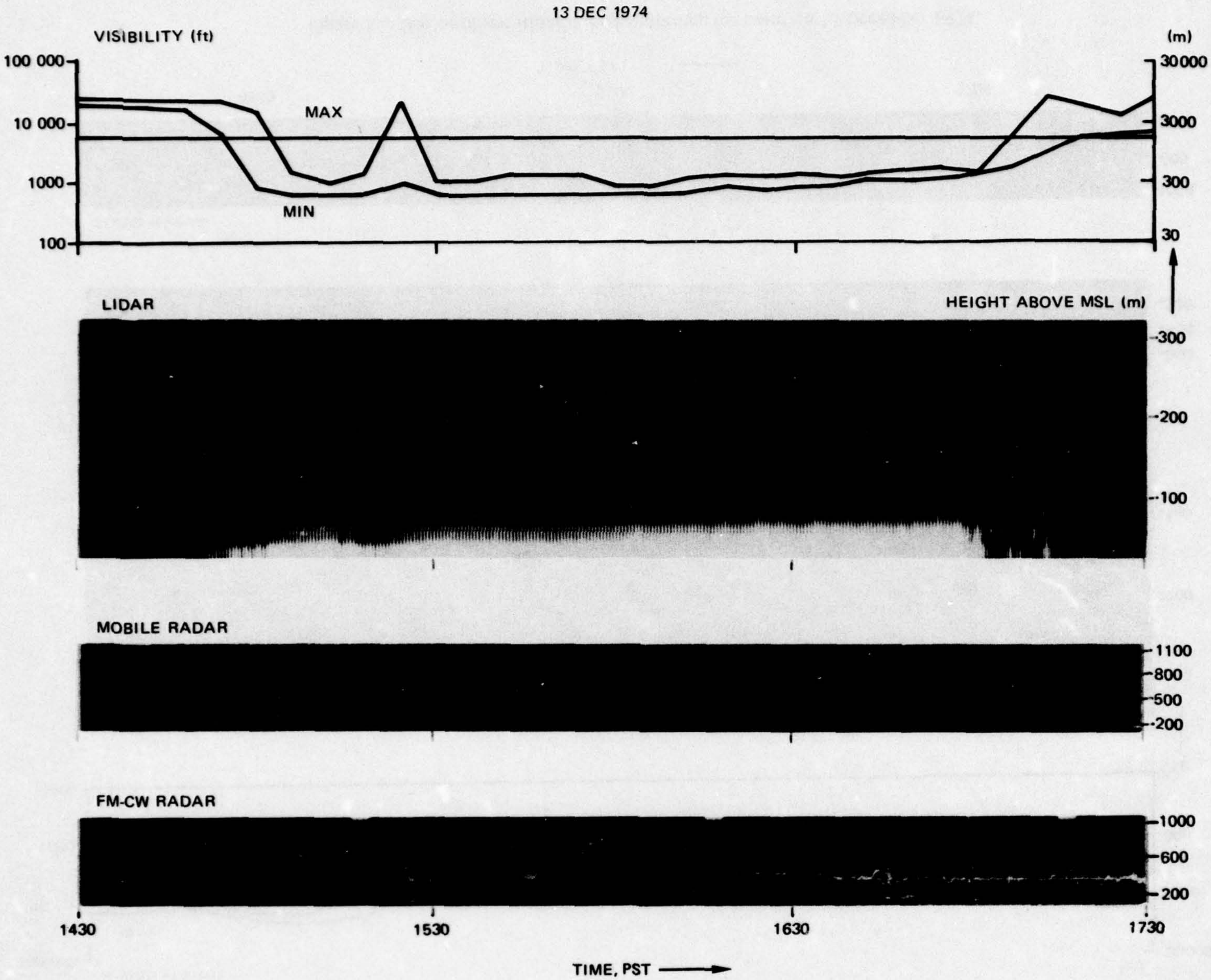

Figure 16. Sensor observations during an evening fog event on 13 December 1974.

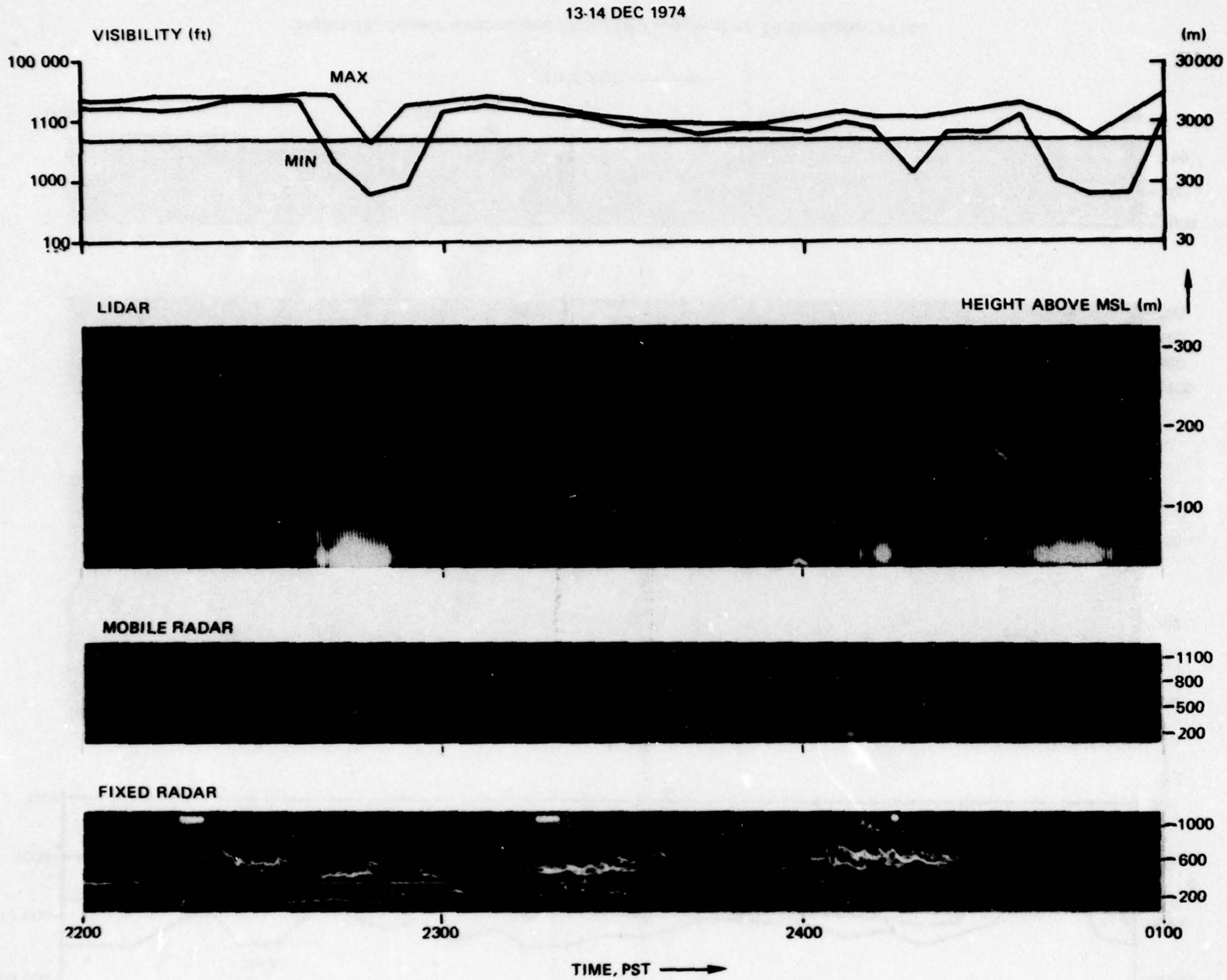

Figure 17. Sensor observations during fog events on 13 and 14 December 1974.

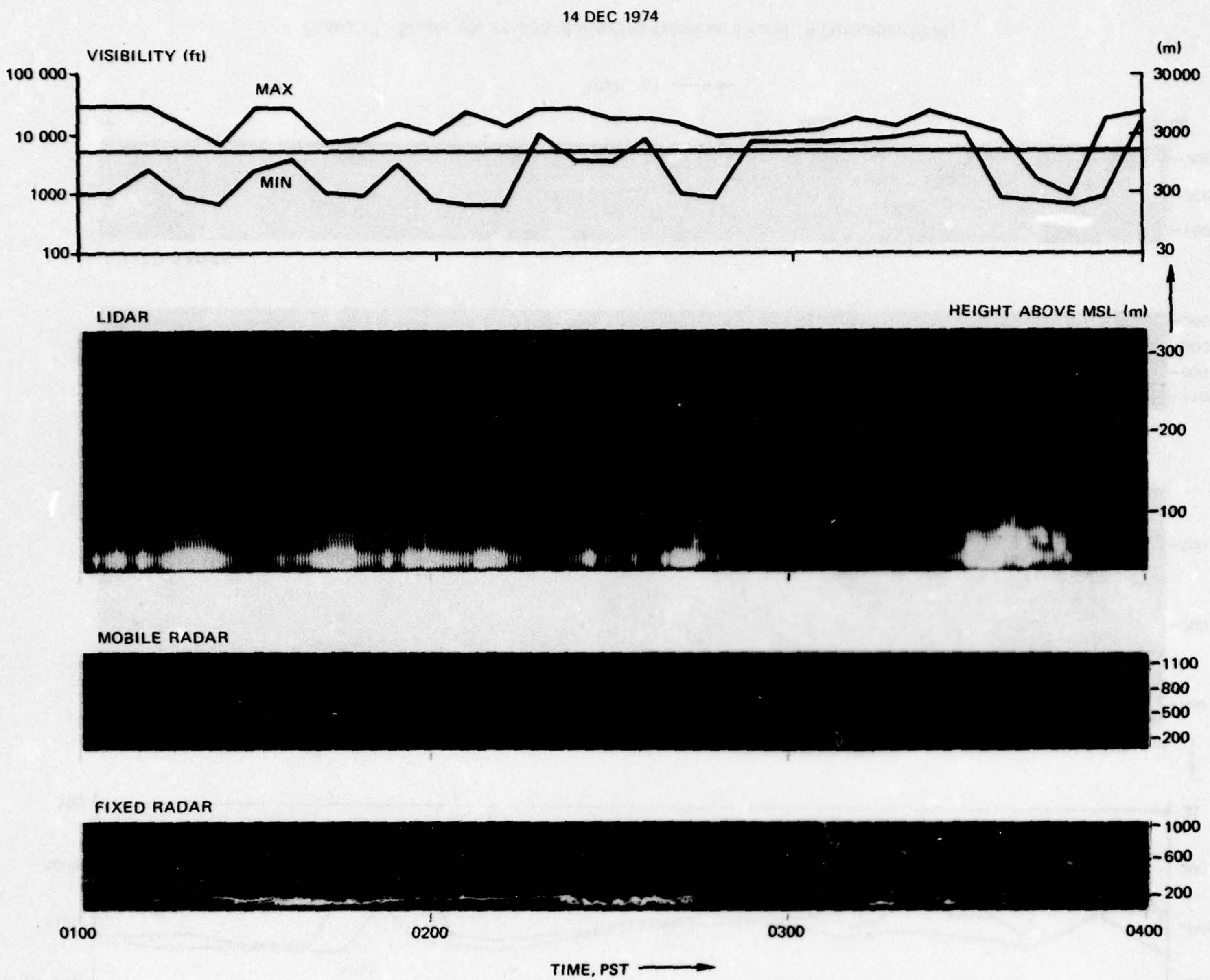

Figure 18. Sensor observations during first fog event on 14 December 1974.

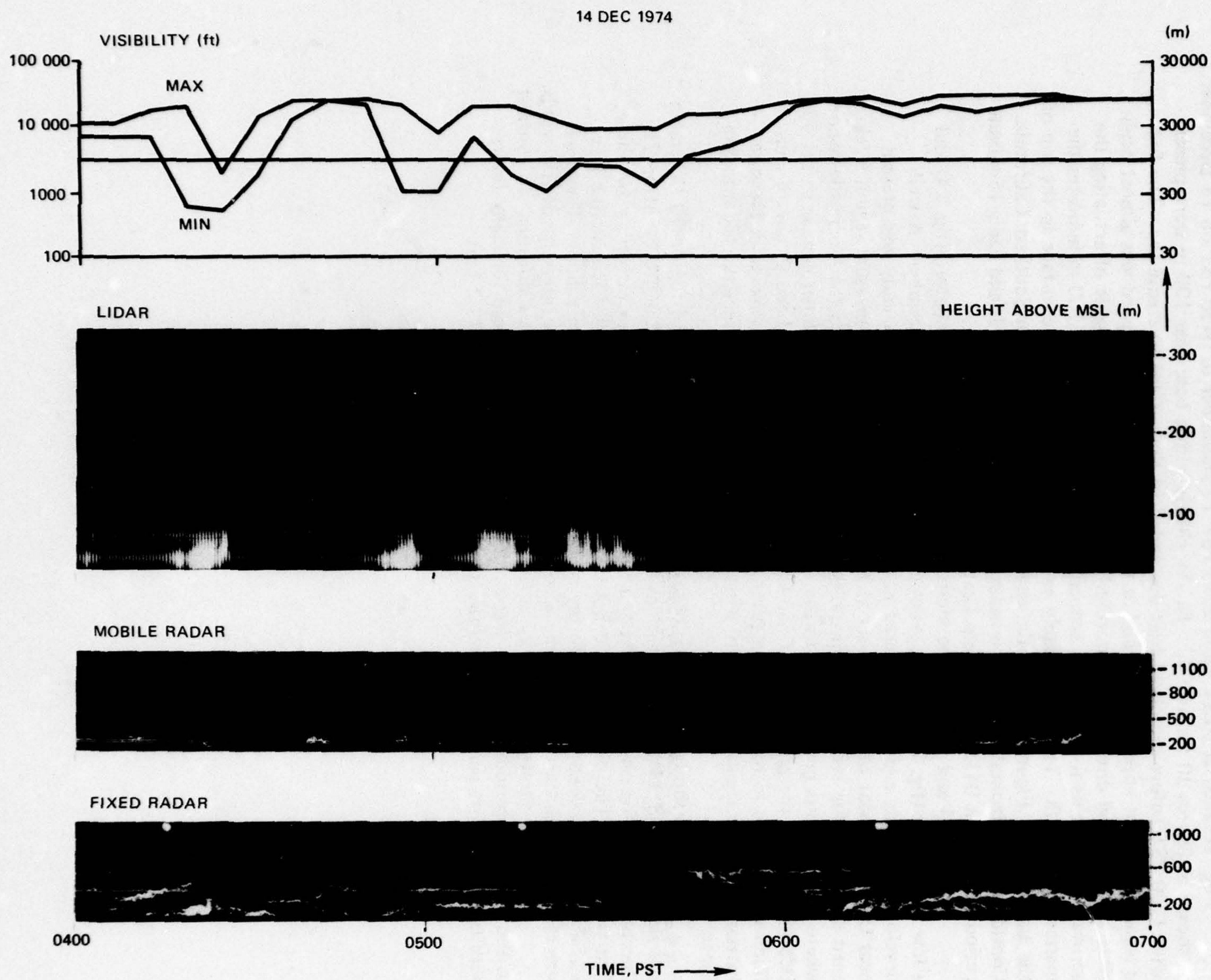

Figure 19. Sensor observations during second fog event on 14 December 1974.

17 TO 22 DECEMBER

Fog prevailed at NELC from 2225 PST 17 December to 0430 PST on 18 December, as shown in figures 20 through 22. Patchy clouds with a base near 100 m were present after 1700 PST before the cloud base descended to the surface to create fog. The fog dissipated without apparently 'lifting' to form clouds. The wind speed was almost negligible and the wind direction was northerly when the wind was capable of actuating the aerovane during this fog event. A semicontinuous radar echo near 200 m indicates the marine layer depth. The fog probably extended vertically from the surface to the top of the marine layer. Figure 23 shows the visibility at four locations near Southern California. Considerable horizontal variability is again exhibited. San Clemente Island had a 15-minute period of fog near 0415 PST. Camp Pendleton had no fog.

Figures 24 and 25 show the mesoscale analysis a few hours before (fig. 24) and a few hours after (fig. 25) the fog event on the night of 17–18 December. A well-developed cyclonic eddy was centered near San Nicolas and a weak eddy was present near Oceanside prior to the fog onset at NELC. The offshore low-pressure region weakened during the fog event and a low-pressure trough extended up to the Oceanside region, where the eddy was present prior to the fog event. Again, in a manner similar to the 13 December event, the region east of San Clemente Island may have been a zone of confluence conducive to fog formation prior to the fog event, and the change in pressure pattern may have created a westerly wind sufficiently strong to advect the fog into San Diego.

Figure 26 shows multisensor observations during the onset of fog on 20 December and figures 27 and 28 show observations during the dissipation of this fog event on 21 December. The fog onset was rapid and the visibility had almost no variability for the first two hours. The dissipation did not involve any post-fog clouds. The marine layer was about 200 m deep according to the radars and acoustic sounder echoes. The wind was essentially calm according to the aerovane, which showed weak intermittent NW winds.

Figure 29 shows the visibility at three stations near Southern California. In contrast to the other fog periods described, fog existed at San Clemente Island for many hours with only one short period of visibilities slightly greater than 2 mi (3.2 km).

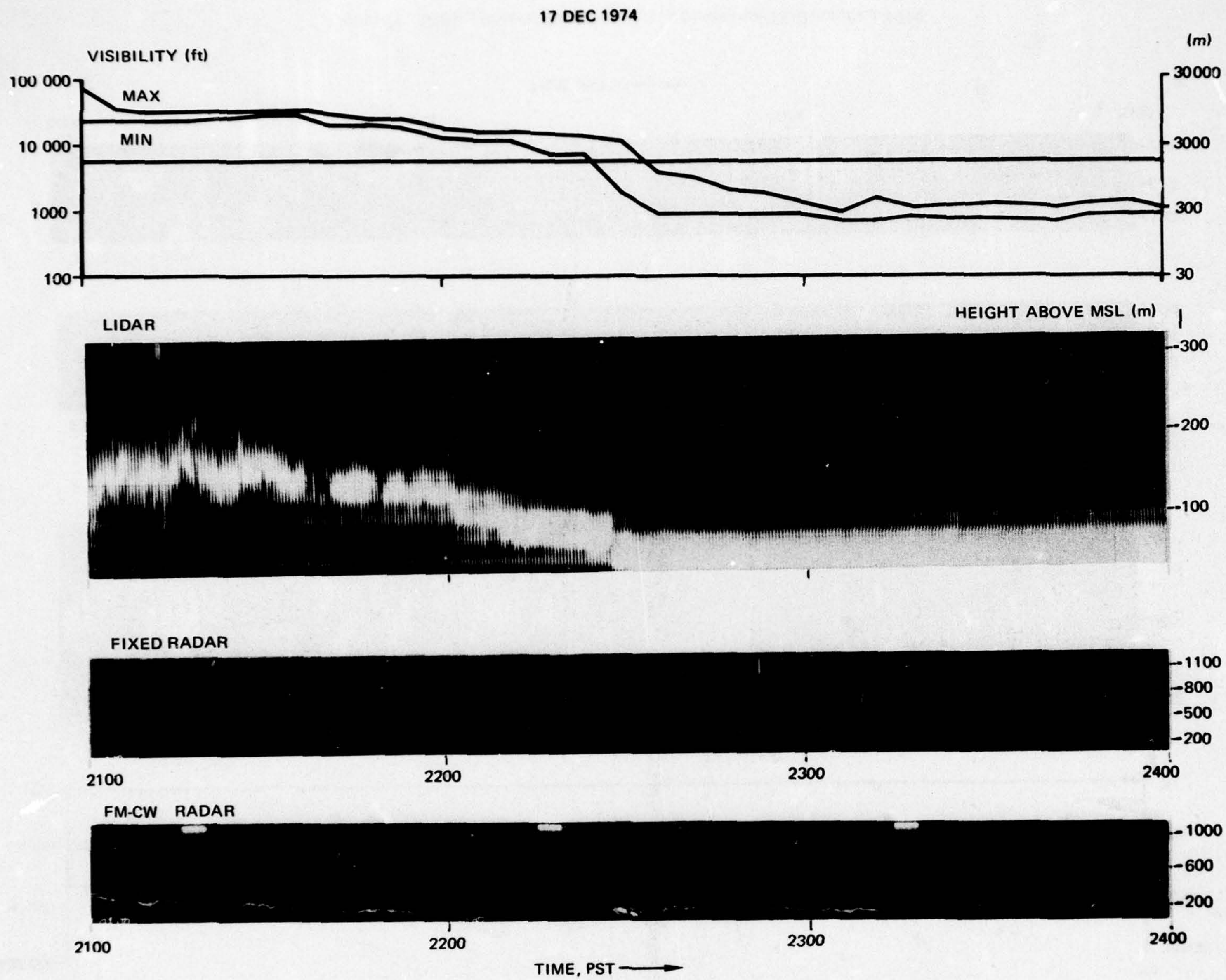

Figure 20. Sensor observations during the onset of a fog event on 18 December 1974.

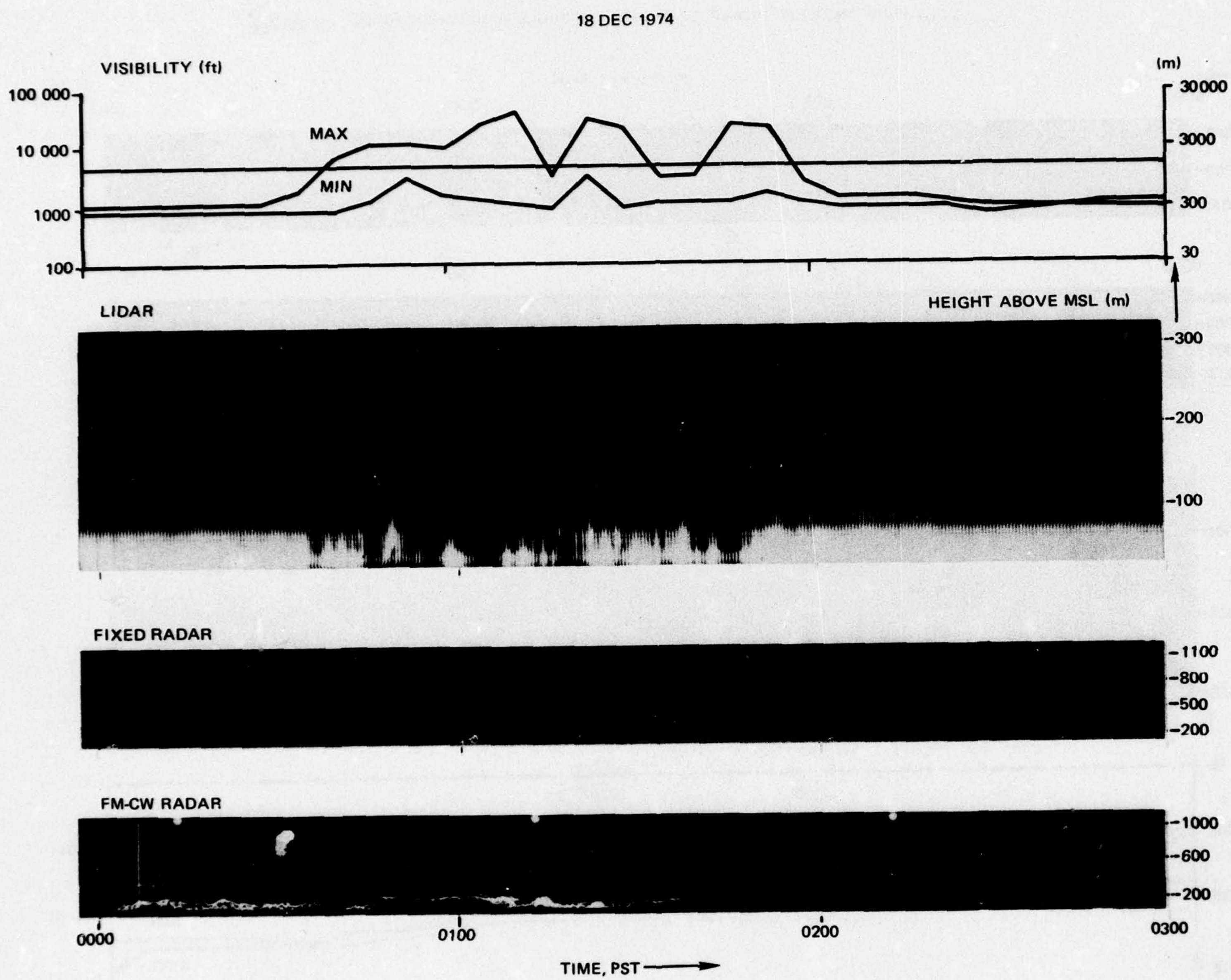

Figure 21. Sensor observations during a fog event on 18 December 1974.

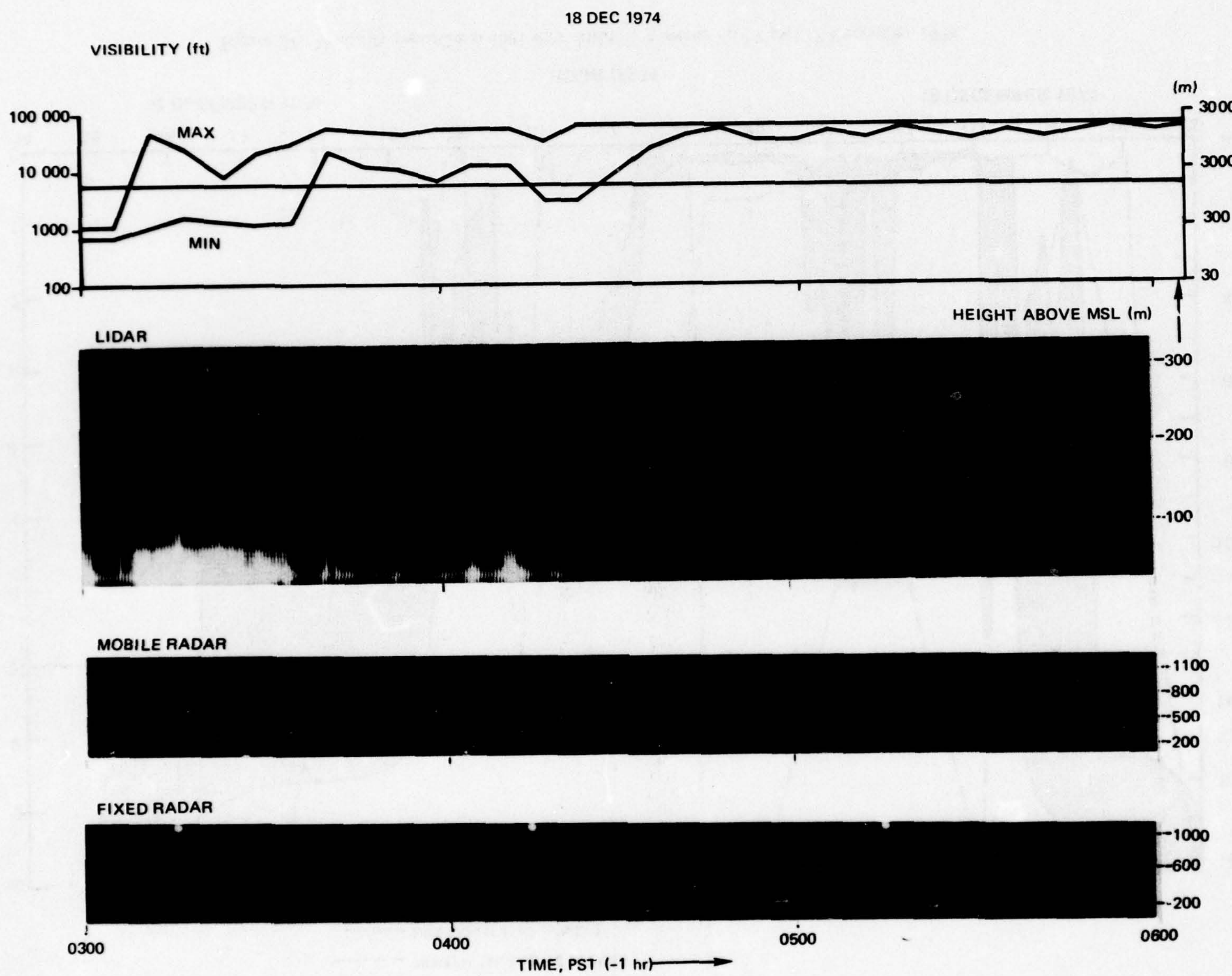

Figure 22. Sensor observations during the termination of a fog event on 18 December 1974.

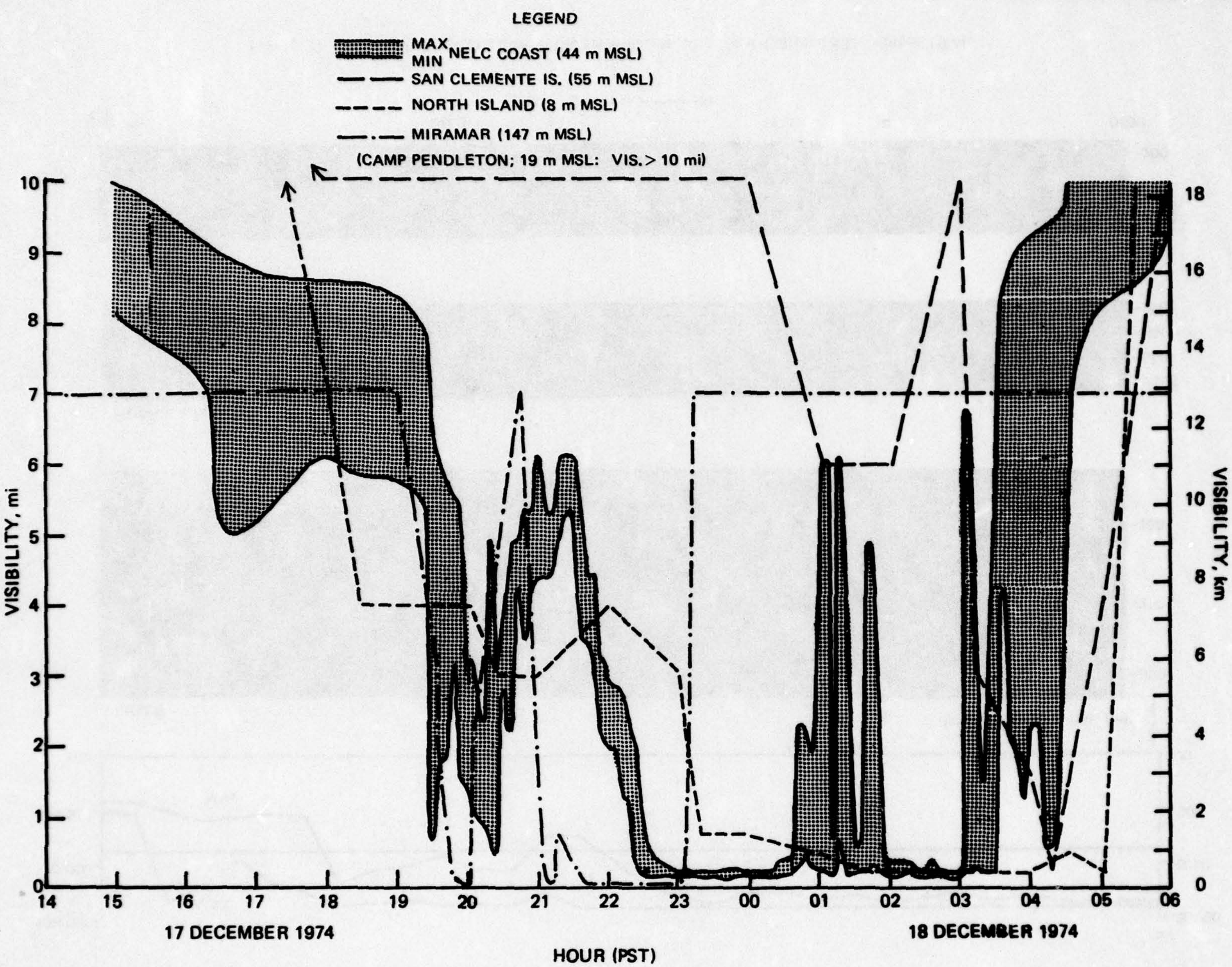

Figure 23. Visibility reported at four sites during fog events on 17 and 18 December 1974.

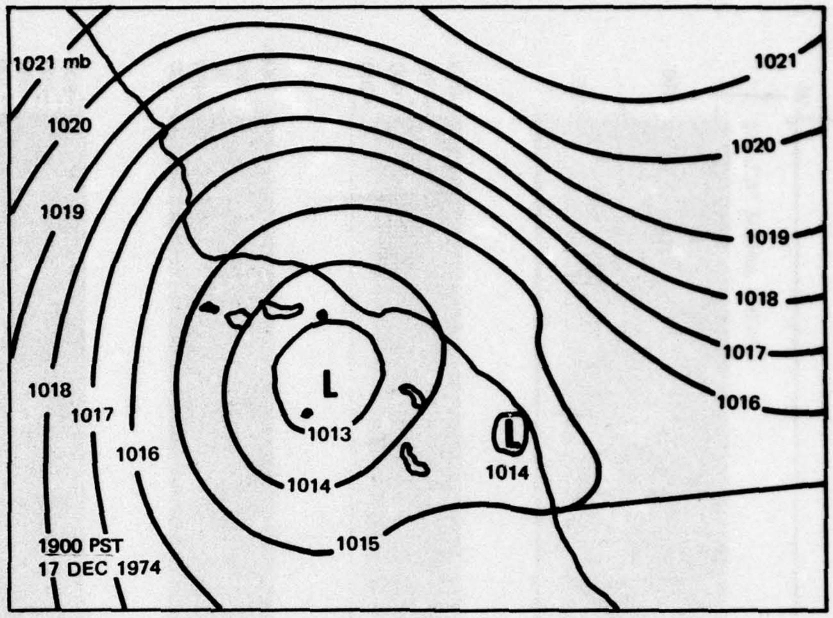

Figure 24. Mesoscale analysis of the sea-level pressure at 1900 PST on 17 December 1974.

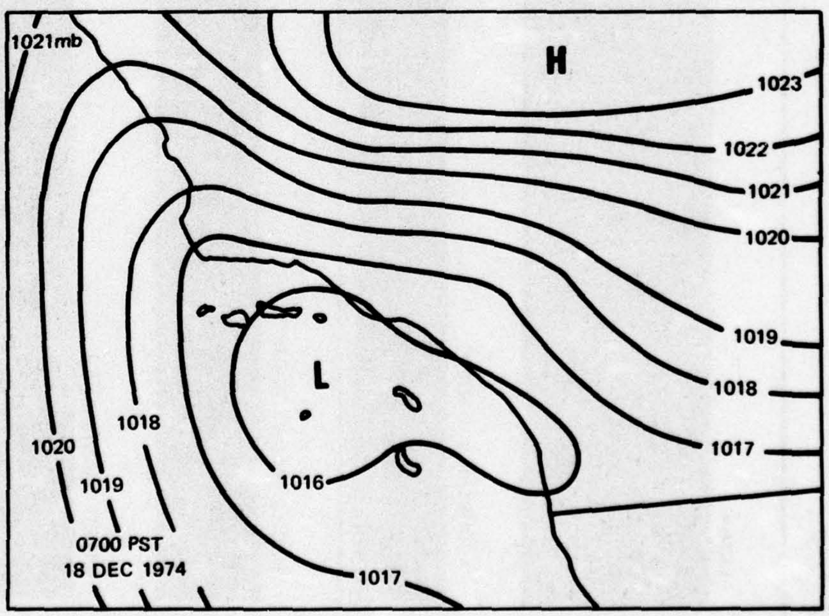

Figure 25. Mesoscale analysis of the sea-level pressure at 0700 PST on 18 December 1974.

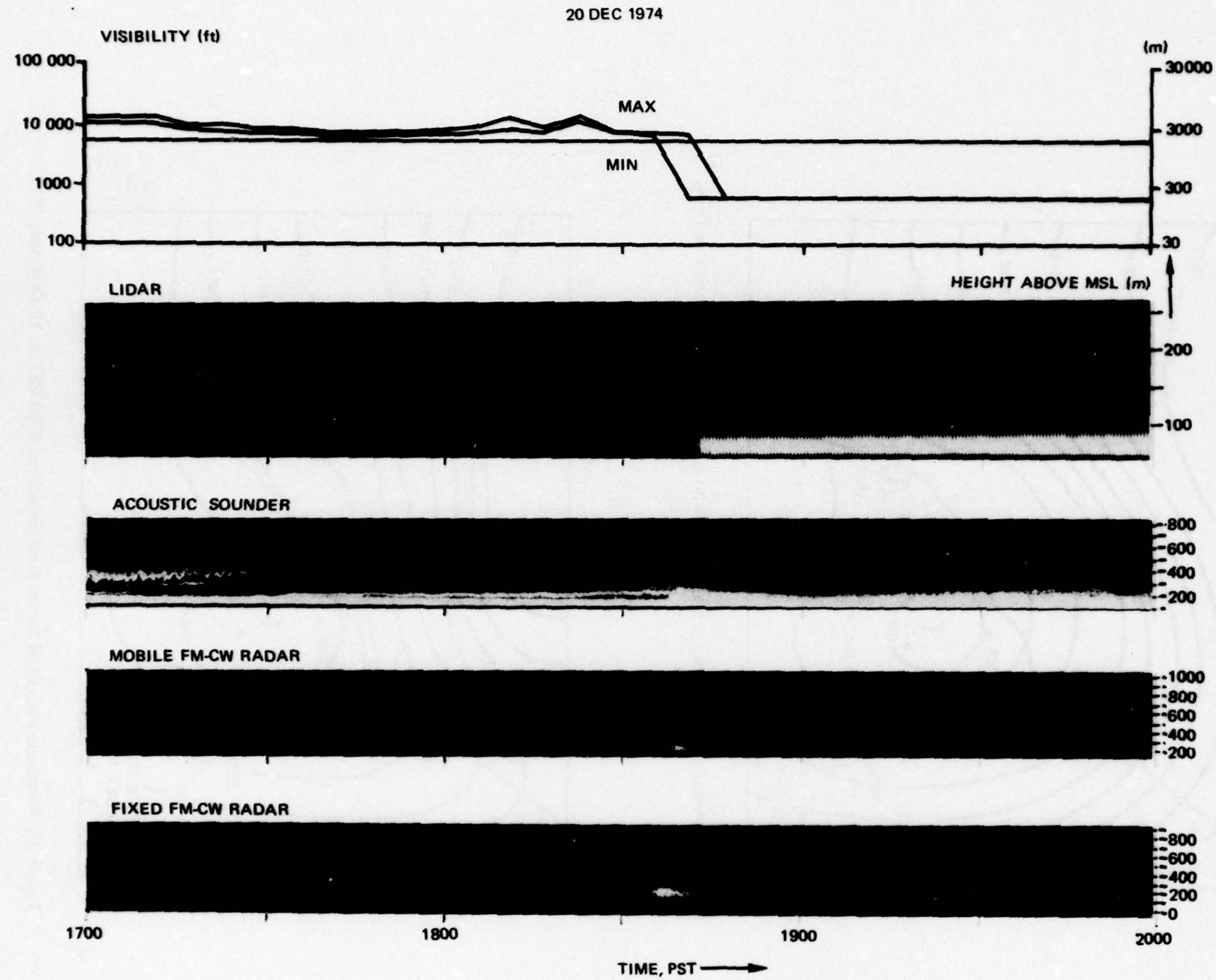

Figure 26. Sensor observations during the sudden onset of fog on 20 December 1974.

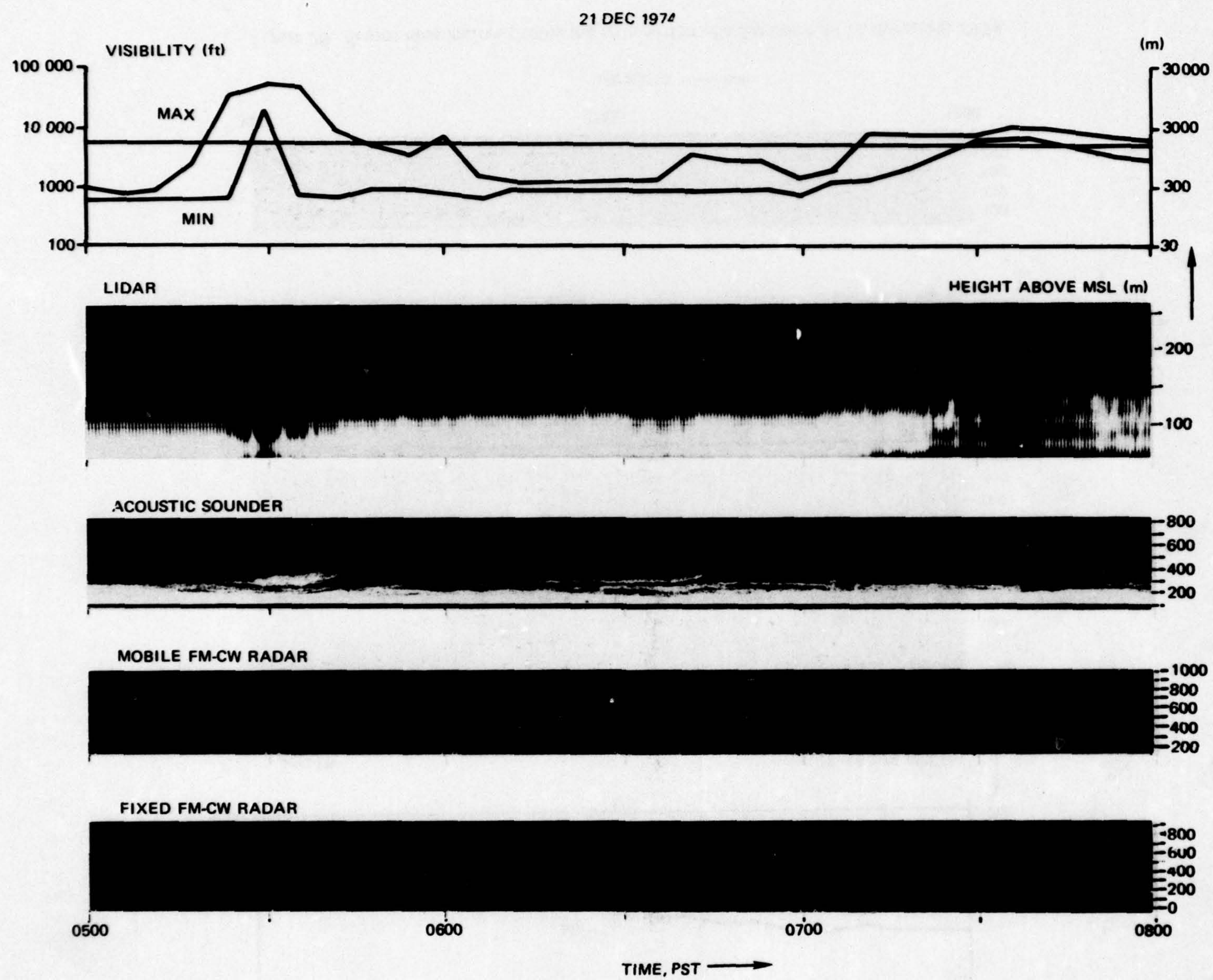

Figure 27. Sensor observations during a fog event on 21 December 1974.

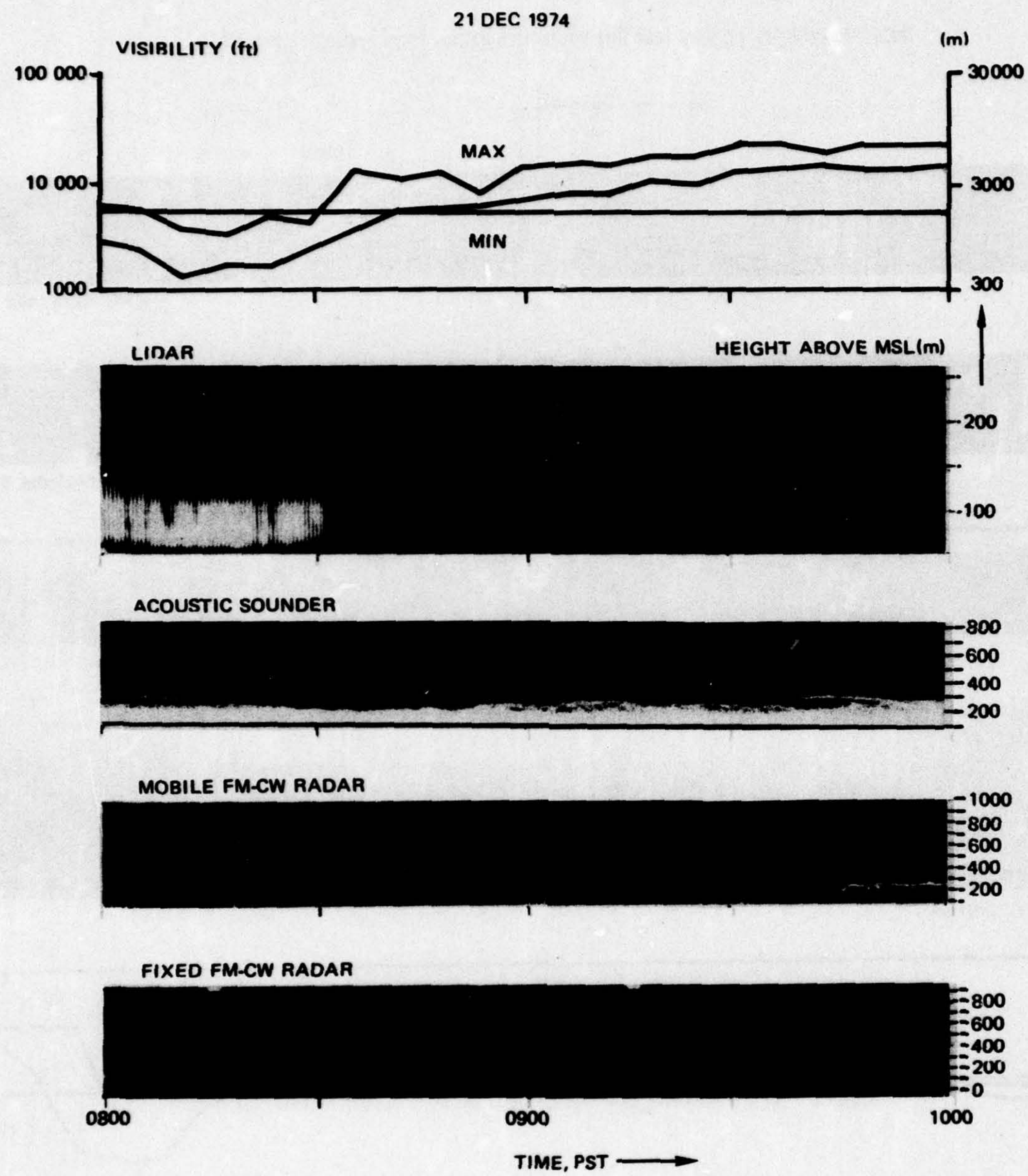

Figure 28. Sensor observations during the termination of a fog event on 21 December 1974.

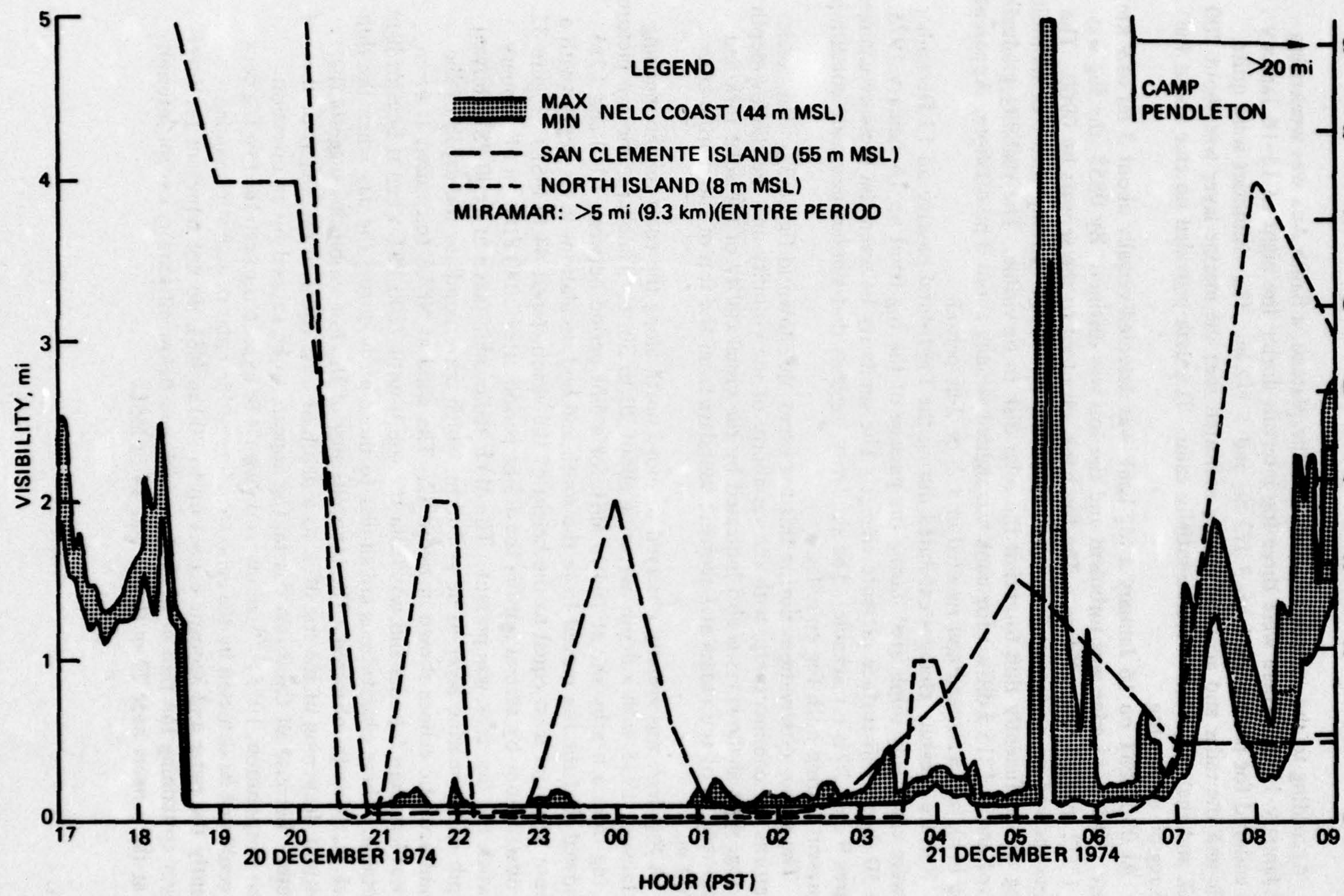

Figure 29. Visibility reported at three sites during a fog event on 20 and 21 December 1974.

OBSERVATIONS OF 16–18 JANUARY 1975

According to the surface pressure over the plateau, a Santa Ana was weakening on 15 January 1975. There were three fog intervals during the night of 15–16 January which endured for periods of 1 hr, 3 1/2 hr, and 1 1/2 hr. The visibilities were quite variable and the radar and acoustic echoes indicated that the marine layer was about 200 m thick and that the winds were essentially calm. The data provided no clue about the source region of the fog.

At 0800 PST on 16 January a fog bank was detected visually about 3 mi (4.9 km) offshore. The front edge was turbulent and the top was distinct. By 0855, the fog was about 1 1/2 mi (2.4 km) offshore. The fog bank advanced to the sensors by 0900. The aerovane showed no evidence of wind and there was no change in temperature or humidity. The fog was sufficiently thin to permit the solar disk to be visible. The visibility gradually improved and at 1215 a diffuse fog bank was sighted visually about 3 mi offshore. Apparently the fog bank had advanced and receded in a 2- or 2-hr period.

Surface pressure changes exhibited during the fog-frontal passage on 13 December 1974 were essentially duplicated during the passage of the fog front on 16 January 1975. Figure 30 shows this surface pressure change. The similarity between the pressure changes in figures 9 and 30 is remarkable. The similarity suggests that similar mesoscale conditions were present during both fog episodes.

The sensor observations during this fog event are shown in figure 31. The weak lidar returns are commensurate with the variability of the visibility and the shallow depth of the fog. The shallowness is also indicated by the visual clarity of the solar disk and the echo returns of the radars and acoustic sounders from the top of the marine layer near 200 m.

A fog deck was visually observed to move north along the coast on the morning of 18 January 1975 with a depth averaging about 20 to 30 m. Time-lapse motion pictures of the fog from a nearby site at 104 m MSL for a 5-hr period between 1210 and 1715 PST showed that the fog moved from the south and had oscillations in its depth (with a maximum height at least equal to the height of the visiometer at 44 m MSL). Figure 32 shows observations by several sensors for a 3-hr period after 2030 PDT on 18 January 1976 when the fog deck was present. The MYF radiosonde taken at 1600 PST showed the depth of the marine layer to be at 200 m, which corresponds to the depth of the radar and acoustic echoes shown in figure 32. The wind at NELC (measured at 55 m MSL) was less than 5 knots and was from the south until 2200 PST when it became light and variable. These observations are similar to those made during the day when the thin fog deck was visually observed. The intermittency of the low visibilities suggests the intermittent deepening of the fog deck to a depth at least equal to the height of the visiometer. Because all California coastal fog appears to be capped by an inversion (Calspan Corporation, 1975)[19a], an inversion would be expected to cap the low fog deck which could not be detected by the echo structure of the radar or acoustic sounder. Apparently the radar and acoustic echoes up to 200 m MSL do not represent the inversion layer containing the thin layer of fog which was below all sensors except intermittently at the sensors near 20 m (lidar) and 44 m MSL.

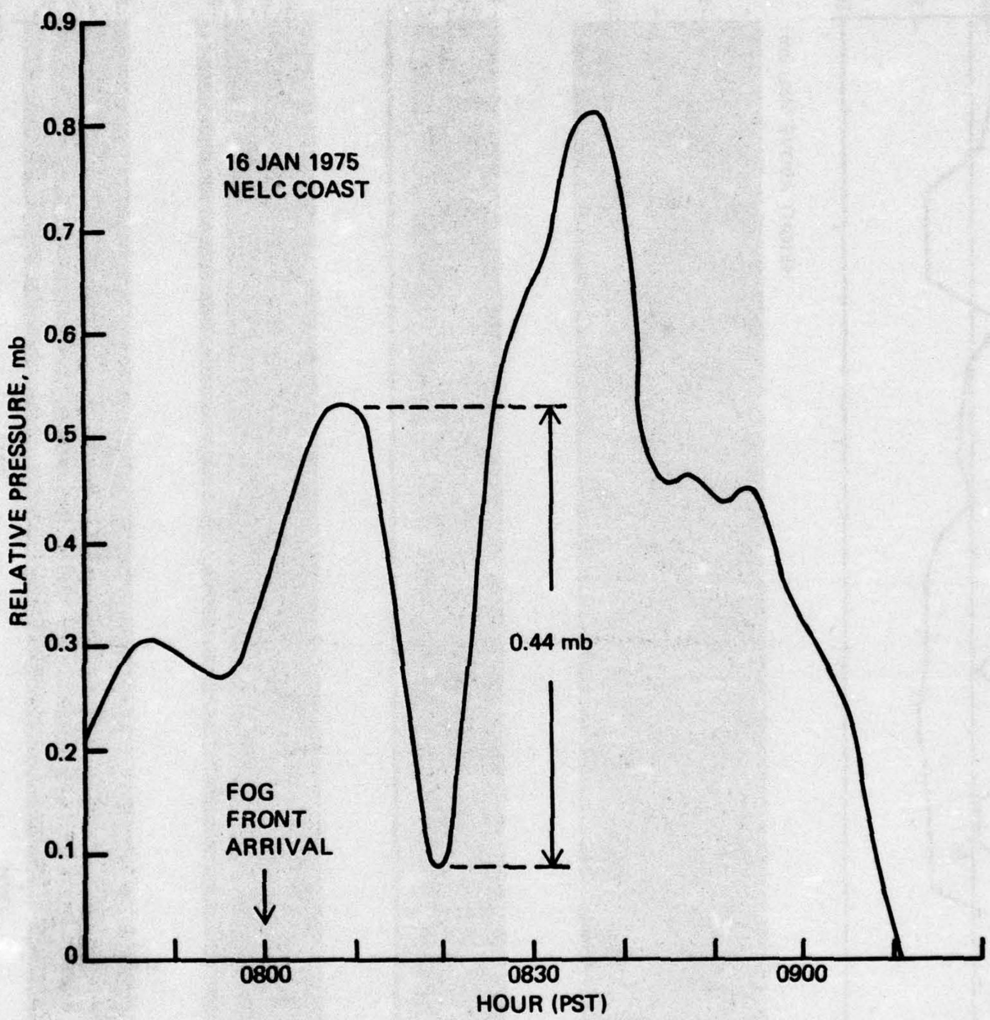

Figure 30. Pressure change following a sudden onset of fog on 16 January 1975.

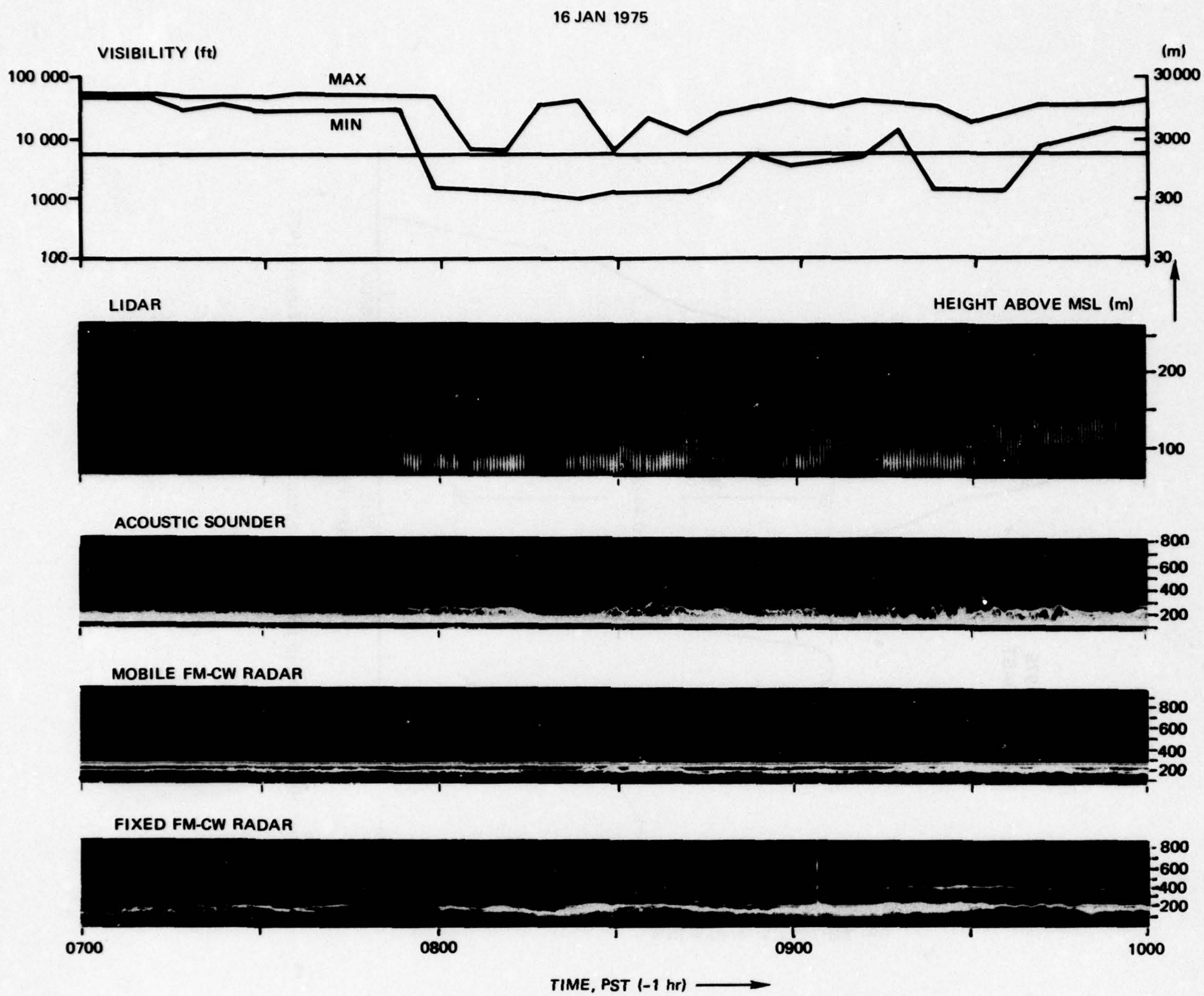

Figure 31. Sensor observations during a fog event on 16 January 1975.

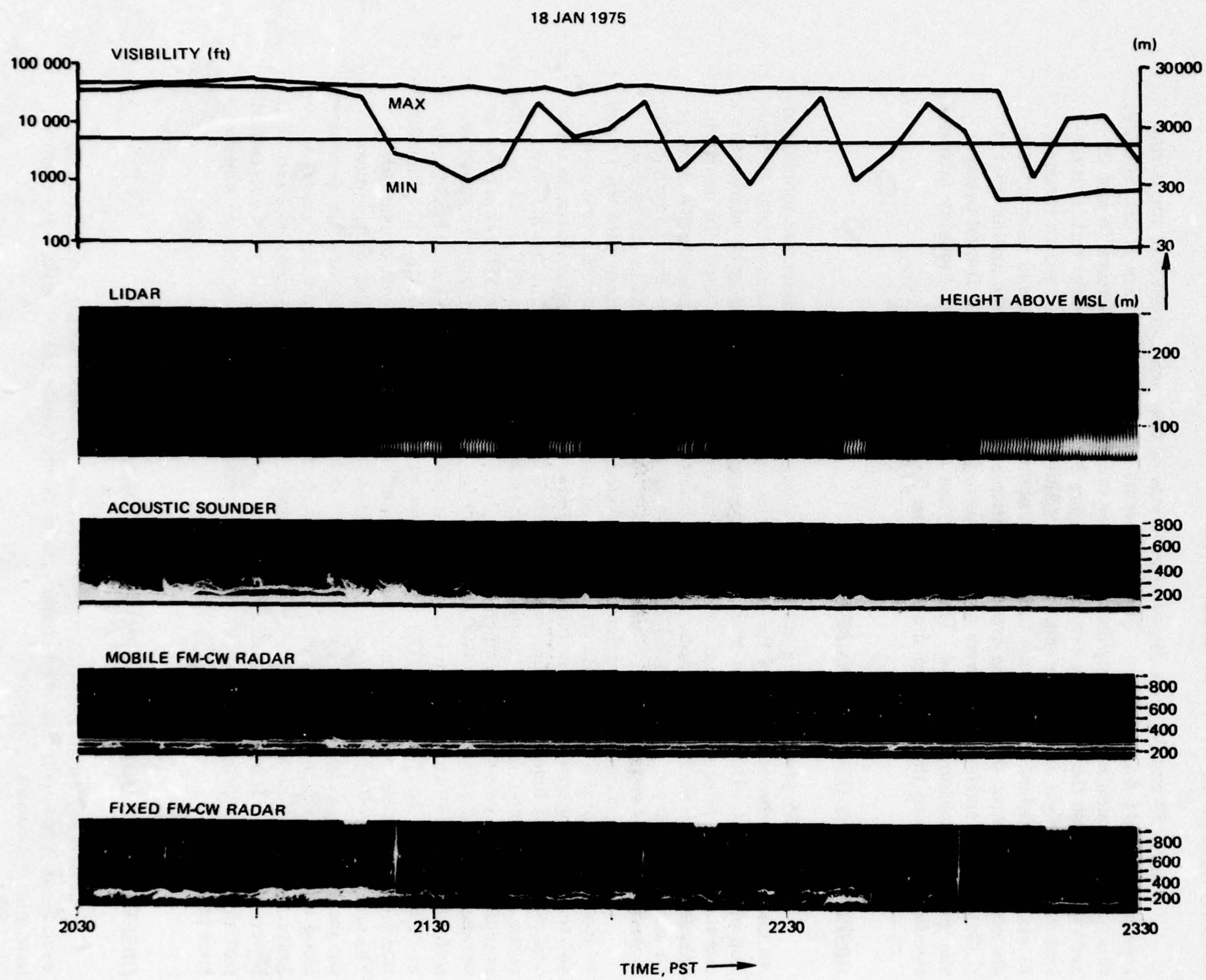

Figure 32. Sensor observations during a fog event on 18 January 1975.

OBSERVATIONS OF 17-19 OCTOBER 1974

Figures 33 and 34 show sensor observations of two sudden onsets of fog during a prolonged Santa Ana condition. These fog events have little variability in the visibility; this behavior is similar to the (sudden onset) fog events depicted in figures 16 and 26 and contrasts with the variability exhibited in figure 31. Differences in the vertical turbulent structure might create differences in the visibility variability. The sensor measurements are insufficient to assess the turbulent structure. The acoustic and radar echoes are not unlike those of other fog events; in particular, the depth of the marine layer is shallow. These sudden onsets were not accompanied by characteristic frontal passage changes in the pressure and wind. The temperature decreased and the humidity increased significantly during the fog onset shown in figure 33.

OBSERVATIONS OF 14 NOVEMBER 1974

Figures 35 and 36 show a morning fog event having a rapid onset and termination. An uncharacteristic deepening of the marine layer was observed at the onset and termination of the event. The significance of this deepening is undetermined. The wind was essentially calm prior to the event although, when intermittently activated, the aerovane indicated an east wind near 2 knots. Thirty minutes before the fog onset, a NW wind at 10 knots commenced and the speed increased to 25 knots at the time the fog terminated. A west wind was sustained until a near-calm condition was approached in the evening.

The surface pressures had decreased considerably over the plateau between 12 and 14 November and the fog episode clearly marked the end of the Santa Ana condition and the beginning of marine layer intrusion inland. Figure 37 shows the change in the vertical profile of temperature and dewpoint during the transition into a marine layer regime. Persistent thick stratus clouds moved onto the coast by 1600 PST on 14 November as indicated by the saturated (temperature and dewpoint equal in the vertical profile) air between 350 and 550 m in the 0400 PST profile on 15 November. Figure 38 shows the surface (44 m MSL) temperature and relative humidity from 1200 PST on 11 November to 1200 PST on 16 November. The figure shows characteristic temperature and humidity traces during the presence of Santa Ana conditions and the marine layer, as marked. The greater variability in the temperature and humidity prior to the fog event indicates the incapability of either the marine layer or the dry Santa Ana air to maintain dominance along the coast. Figure 39 shows the rapid increase in the marine layer depth after a Santa Ana condition which ended in two fog events occurring on the night of 26 to 27 November 1974. The rapid increase in the marine layer depth may have been accelerated partially by the approach of a weak upper-level trough, which probably created some low-level convergence.

OBSERVATIONS DURING NOVEMBER AND DECEMBER 1975

Several fog events occurred in November and December which were related to weak Santa Ana conditions. The characteristics of the sensor echoes reflect the slightly indefinite circulation conditions.

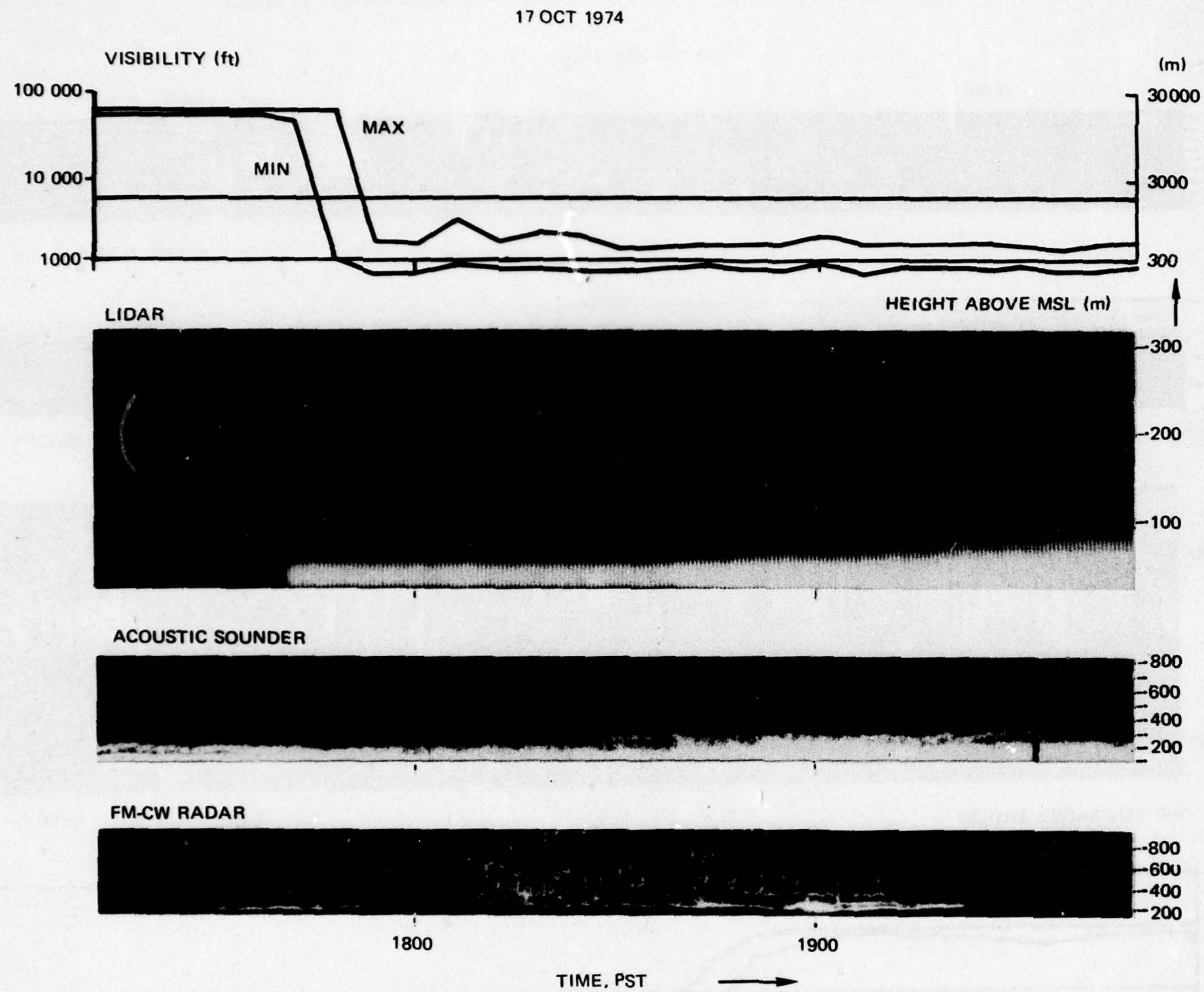

Figure 33. Sensor observations during a sudden onset of fog on 17 October 1974.

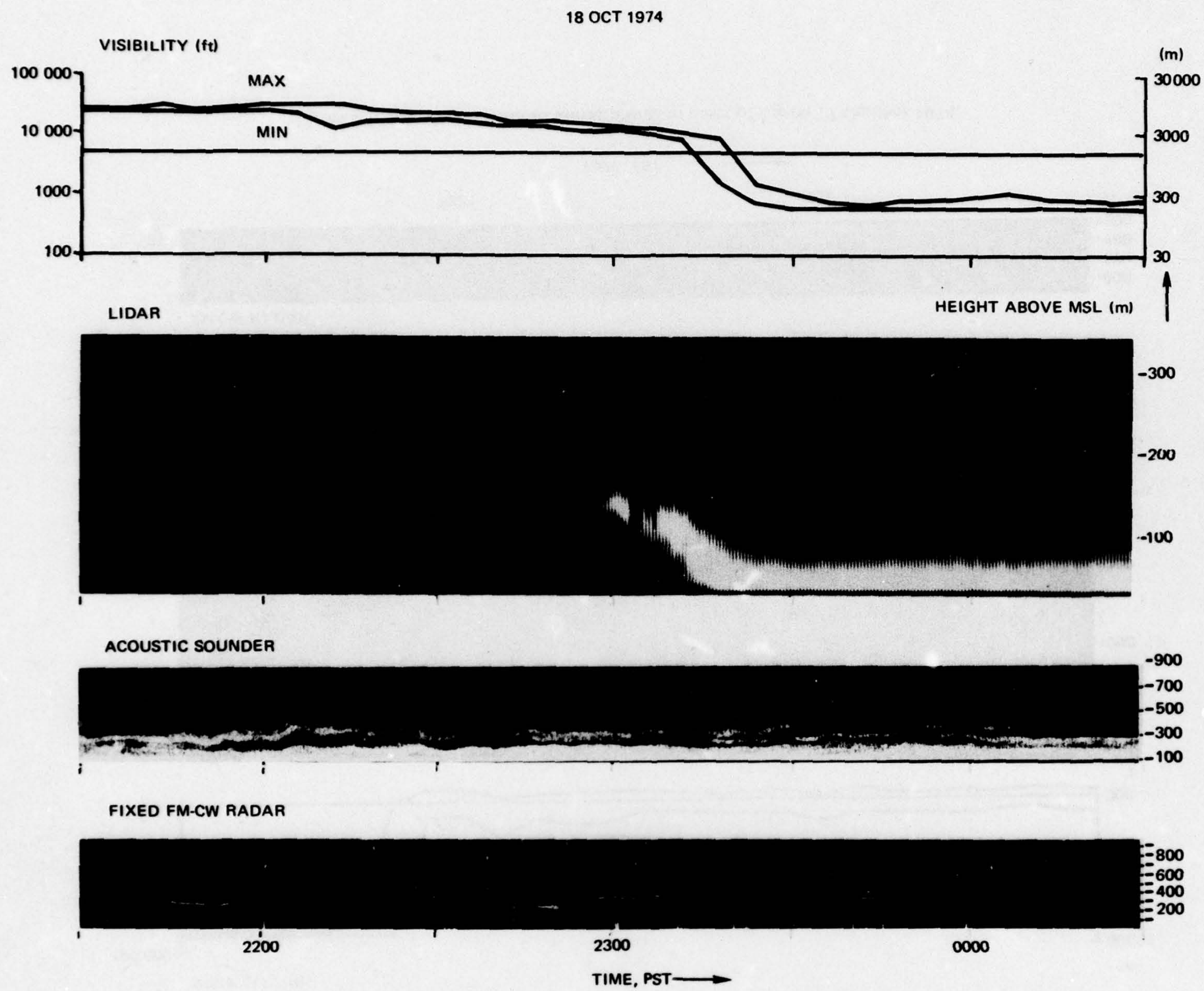

Figure 34. Sensor observations during a rapid onset of fog on 18 October 1974.

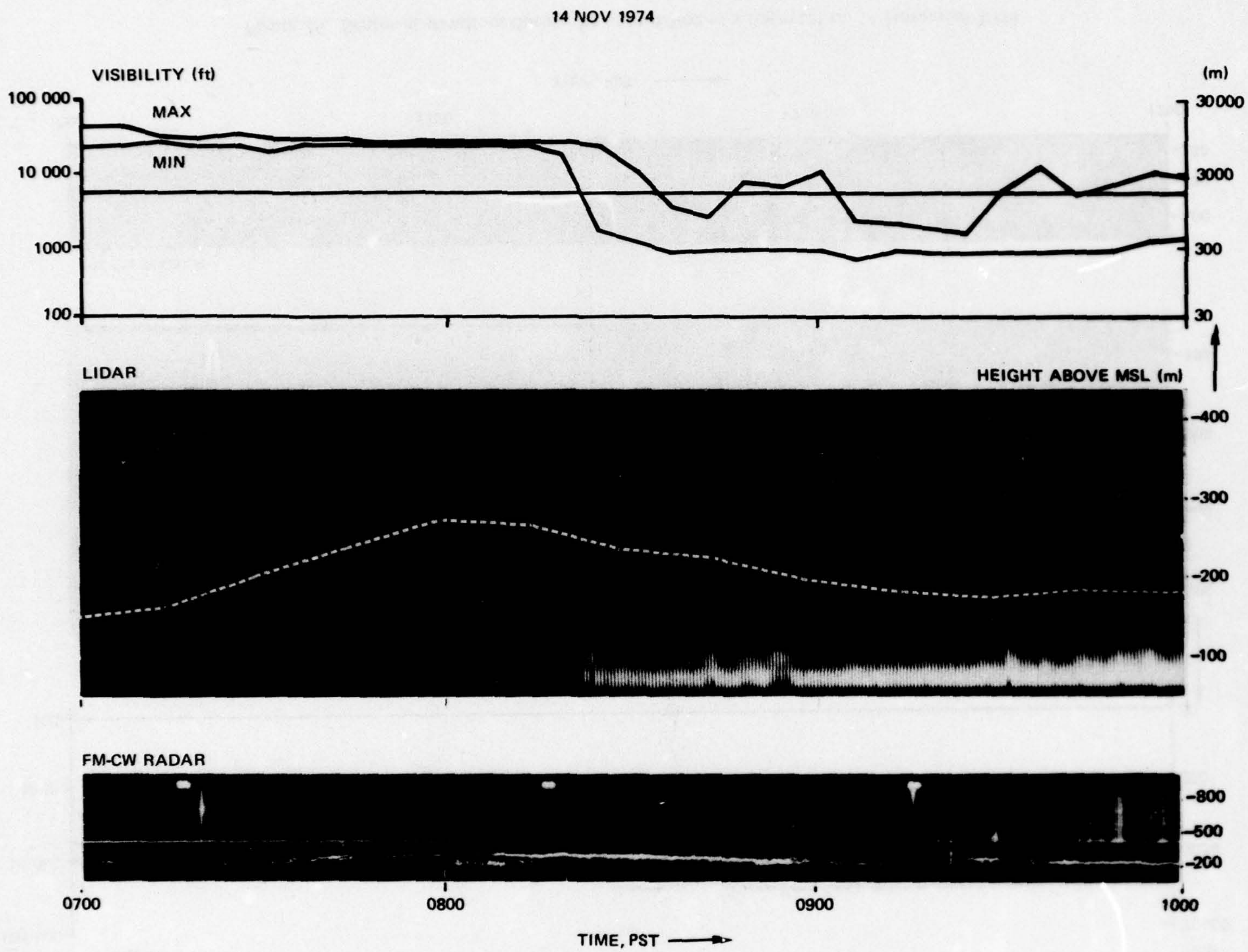

Figure 35. Sensor observations during the onset of a fog event on 14 November 1974.

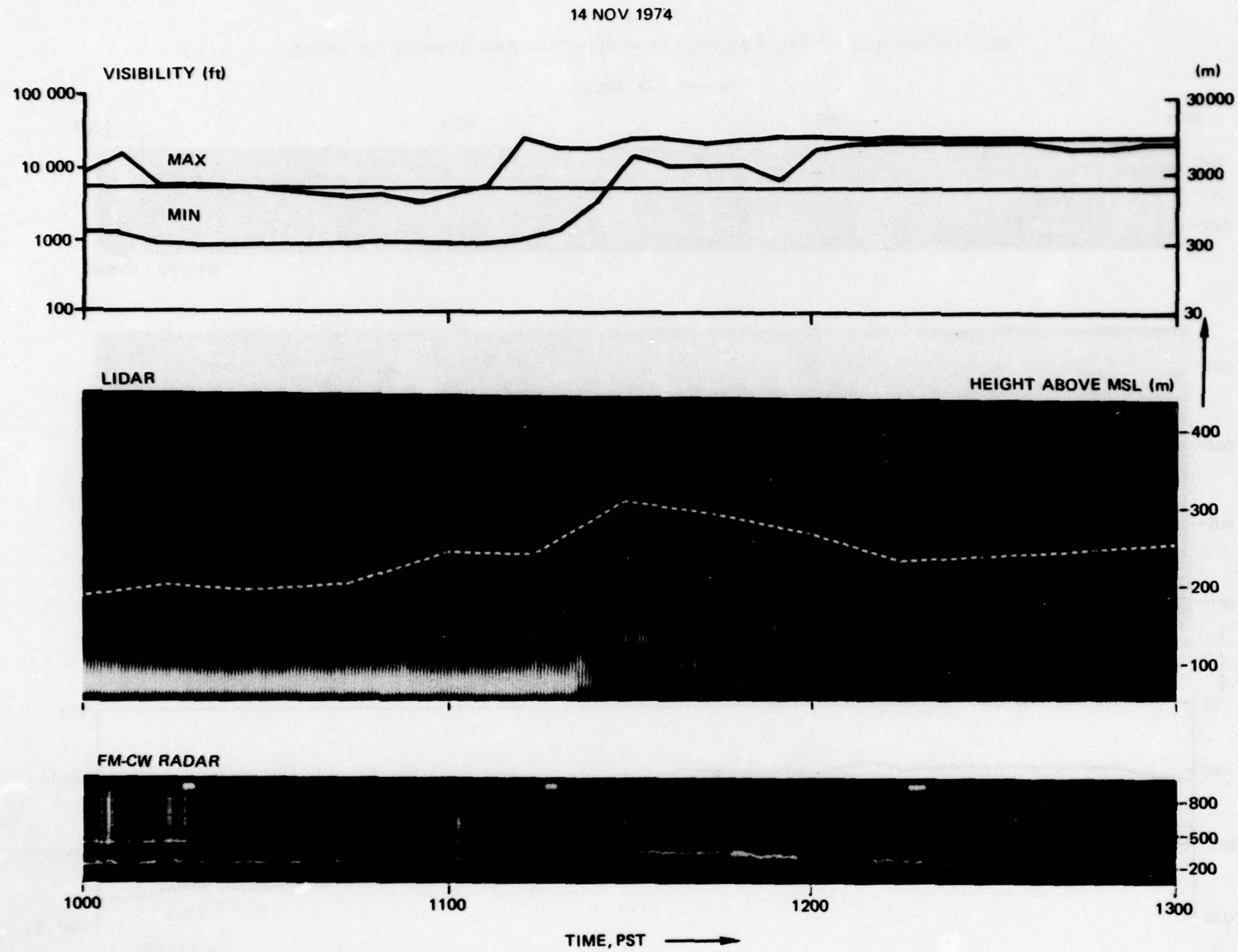

Figure 36. Sensor observations during the termination of a fog event on 14 November 1974.

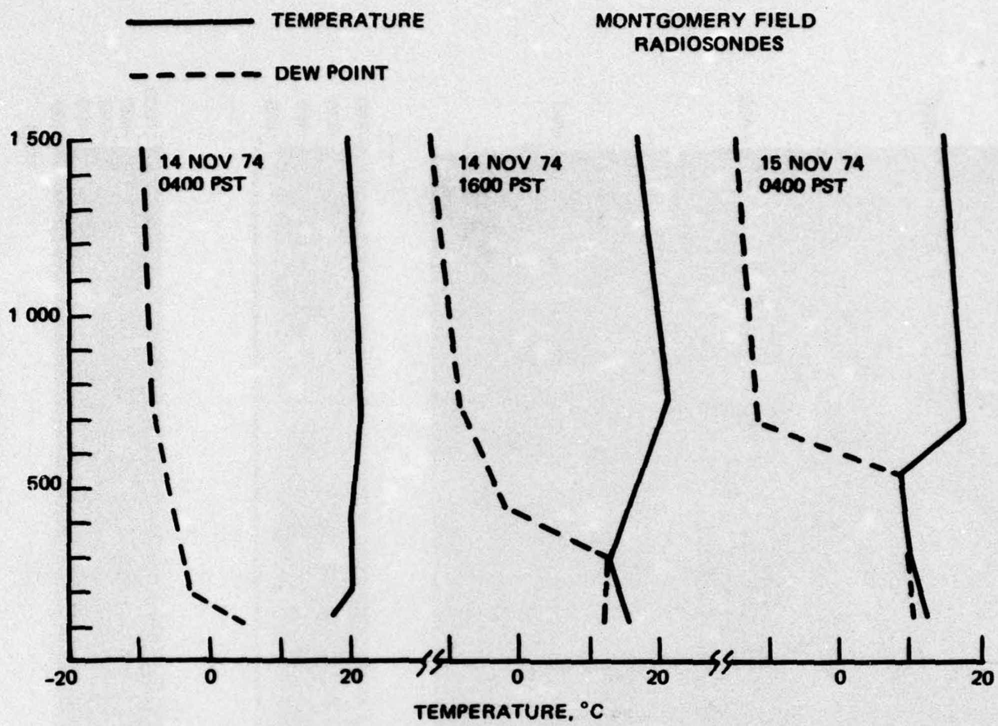

Figure 37. Vertical temperature and dewpoint structure at Montgomery Field during days having fog.

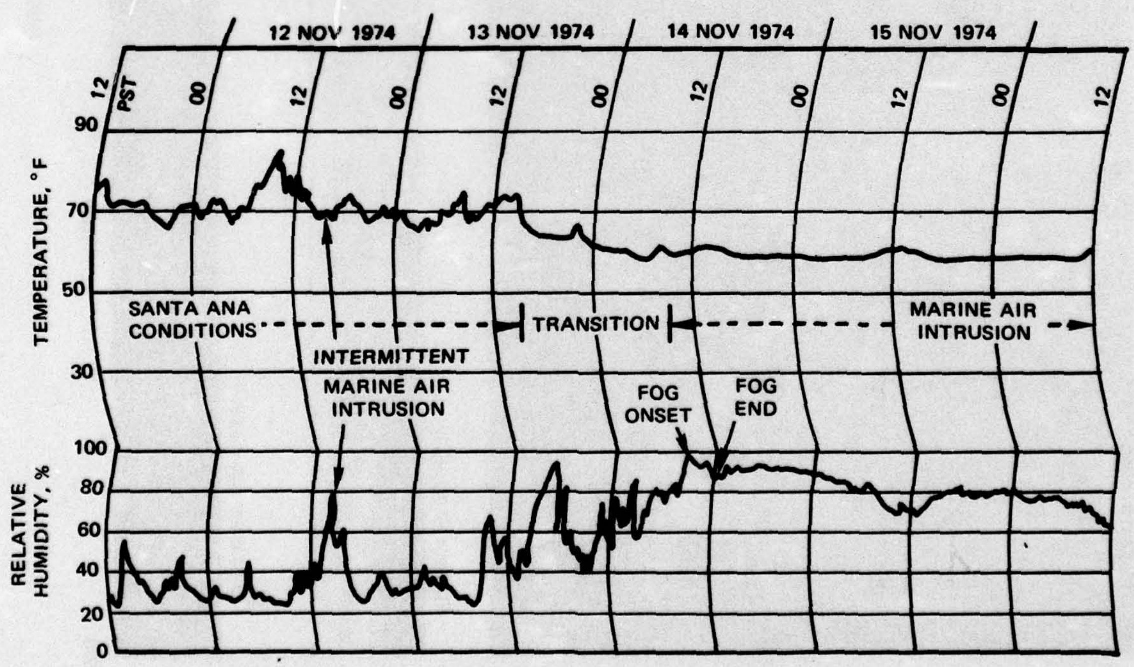

Figure 38. Temperature and relative humidity during Santa Ana conditions, during the transition to the marine layer intrusion and after the marine layer is established on days near a fog event on 14 November 1974.

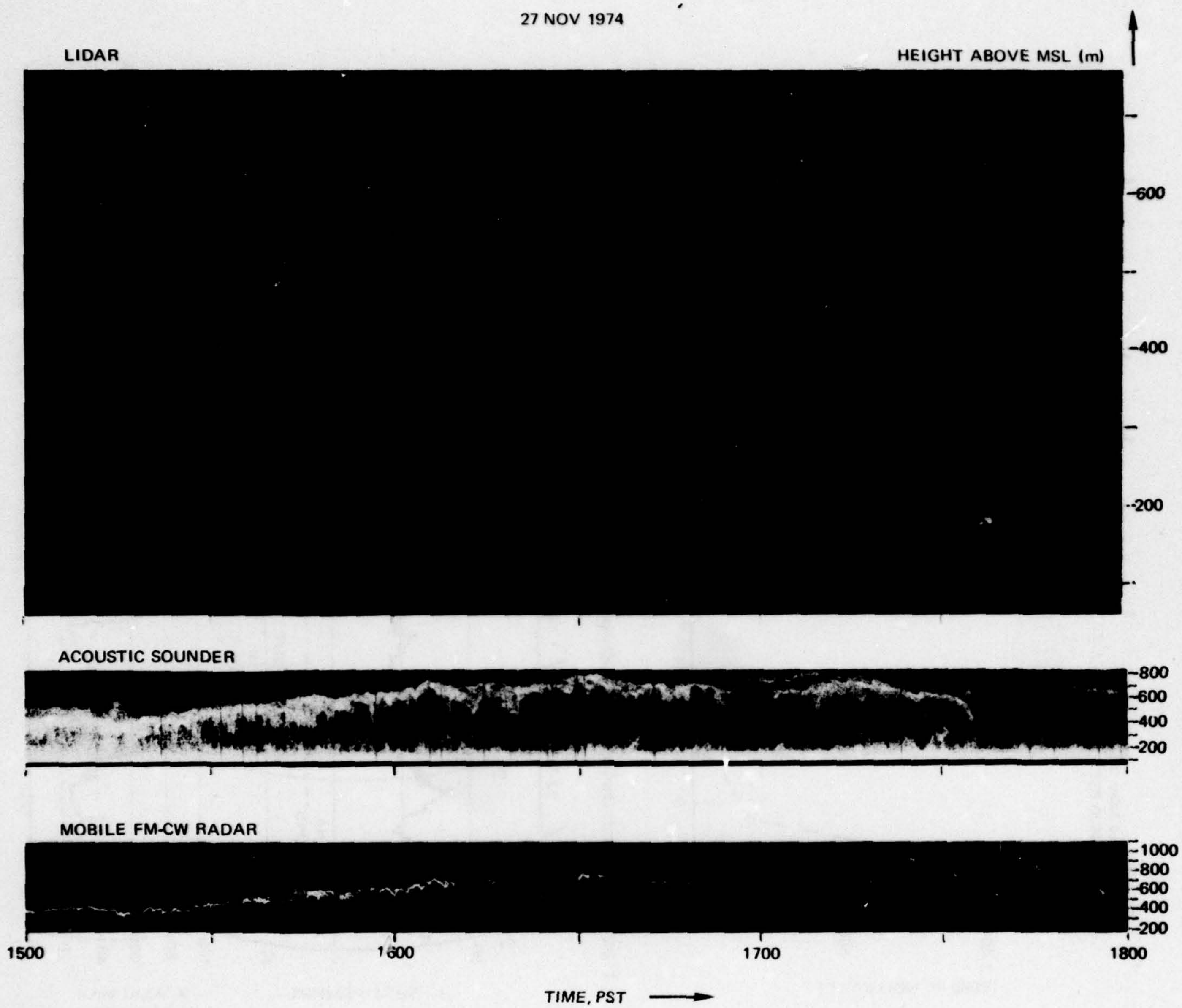

Figure 39. Sensor observations during the rapid deepening of the marine layer on 27 November 1974.

Figure 40 shows a fog event lasting about 45 minutes. The small variability in the visibility and the post-fog stratus clouds are not generally associated with Santa Ana-related fog events. Figure 41 shows a fog event eight hours after the one shown in figure 40. The ceilometer record* suggests that the fog was formed by the descent of the stratus-cloud base.

The fog event depicted in figure 42 occurred with south winds as a trough was approaching the coast from the west. The marine layer deepened rapidly after this fog event. The echoes from the top of the marine layer were uncharacteristically variable for a fog period.

A weak low was present southwest of San Diego on 19 December 1975, while the pressures over the plateau were comparable to a weak Santa Ana. The surface winds were persistently weak and variable and haze restricted the visibility at North Island for hours near this fog event. The sensor echoes were again variable from the top and within the marine layer, as shown in figure 43.

*See NELC TR 1989 for a discussion fo the ceilometer recording technique.

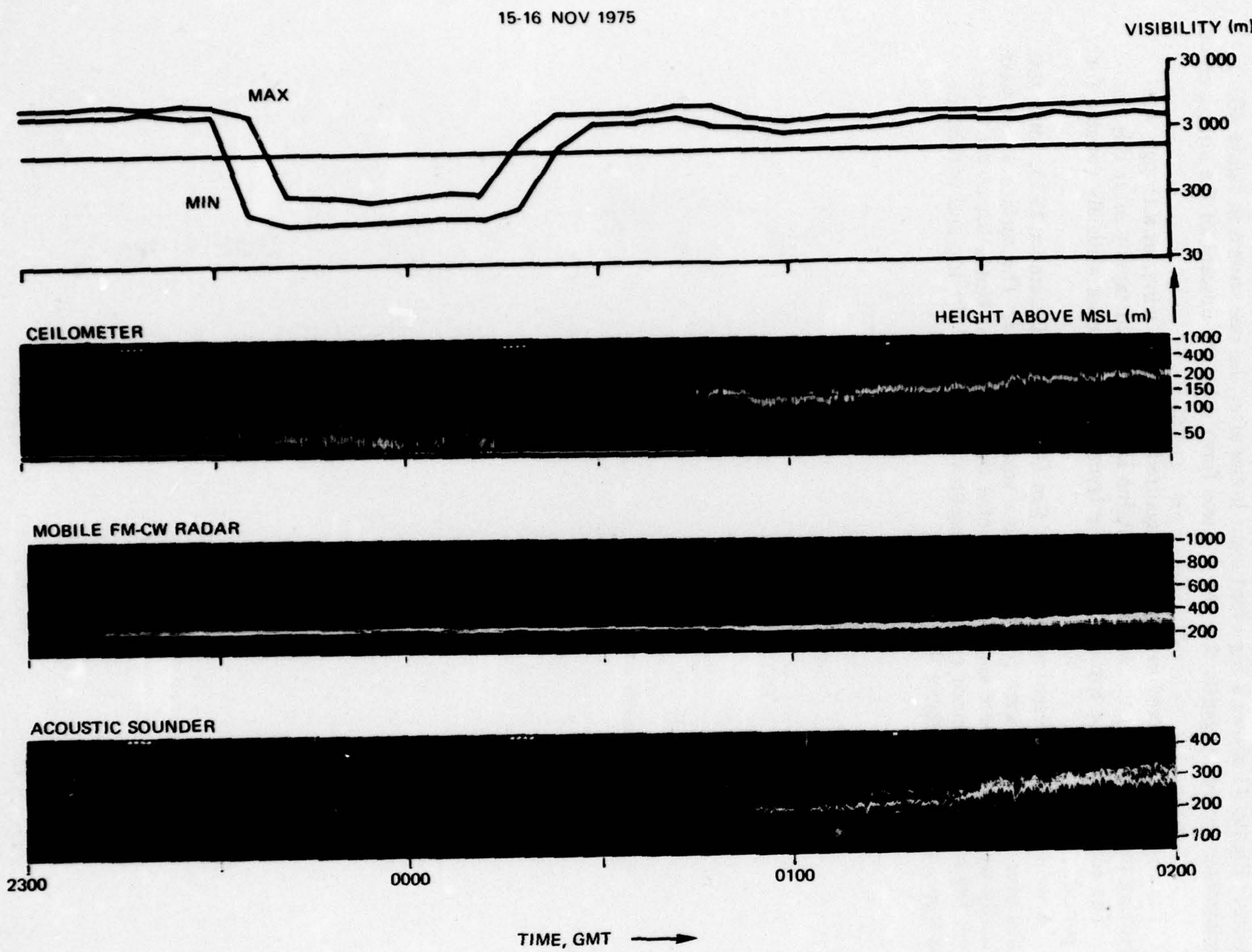

Figure 40. Sensor observations during a fog event on 15 and 16 November 1975. The ceilometer output was recorded by a new filming technique (see NELC TR 1989).

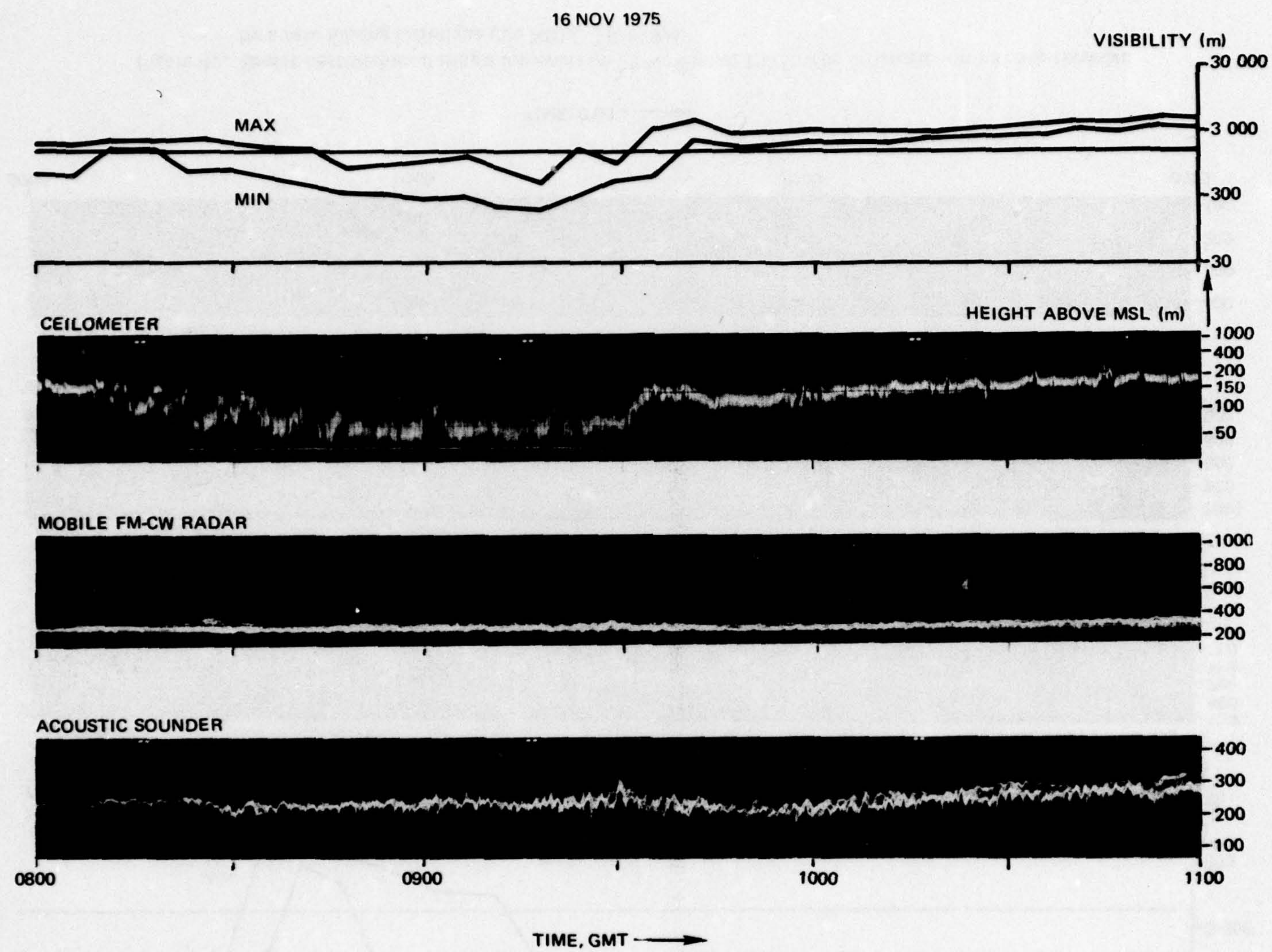

Figure 41. Sensor observations during the termination of a fog event on 16 November 1975. The ceilometer output was recorded by a new filming technique (see NELC TR 1989).

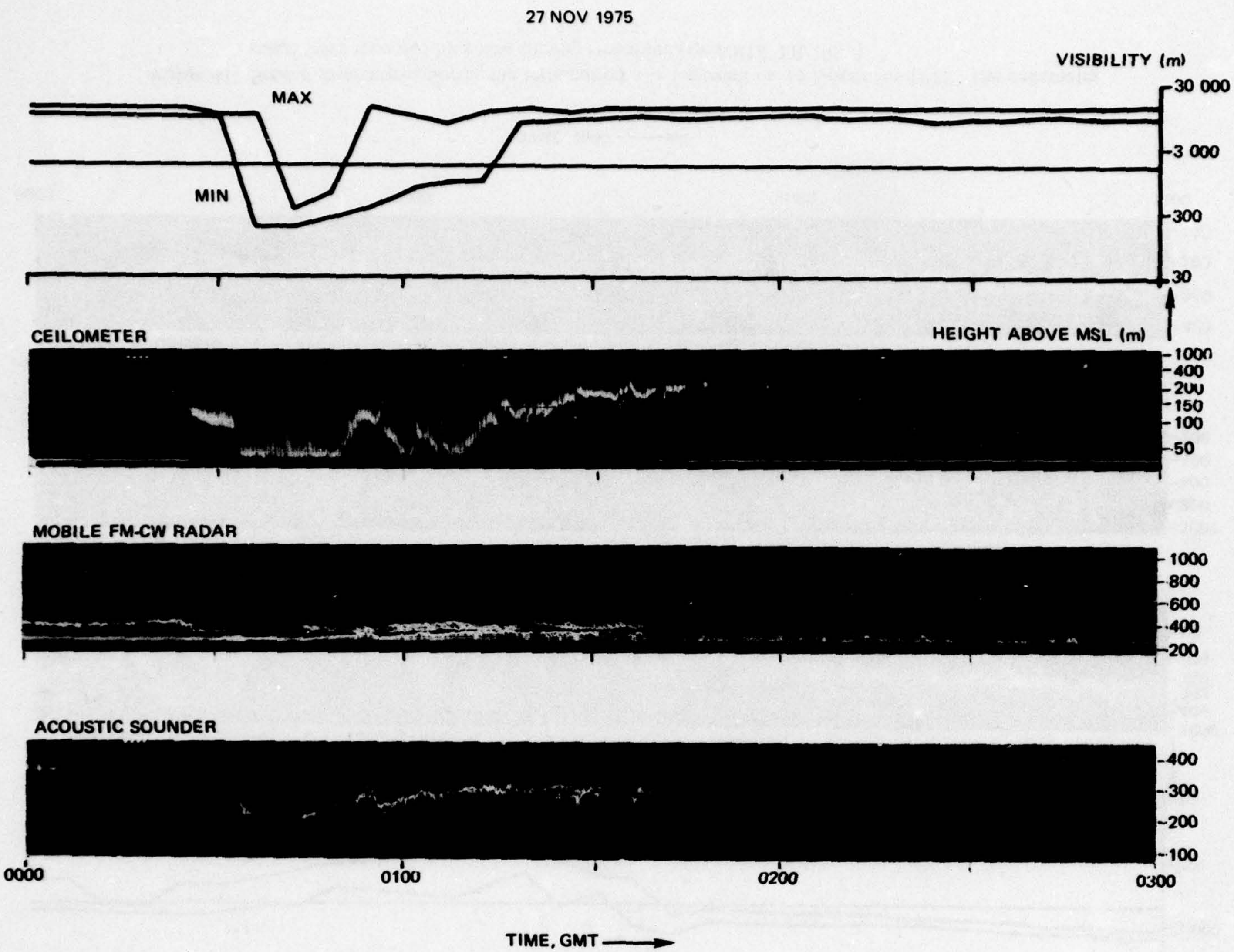

Figure 42. Sensor observations during a fog event on 27 November 1975. The ceilometer output was recorded by a new filming technique (see NELC TR 1989).

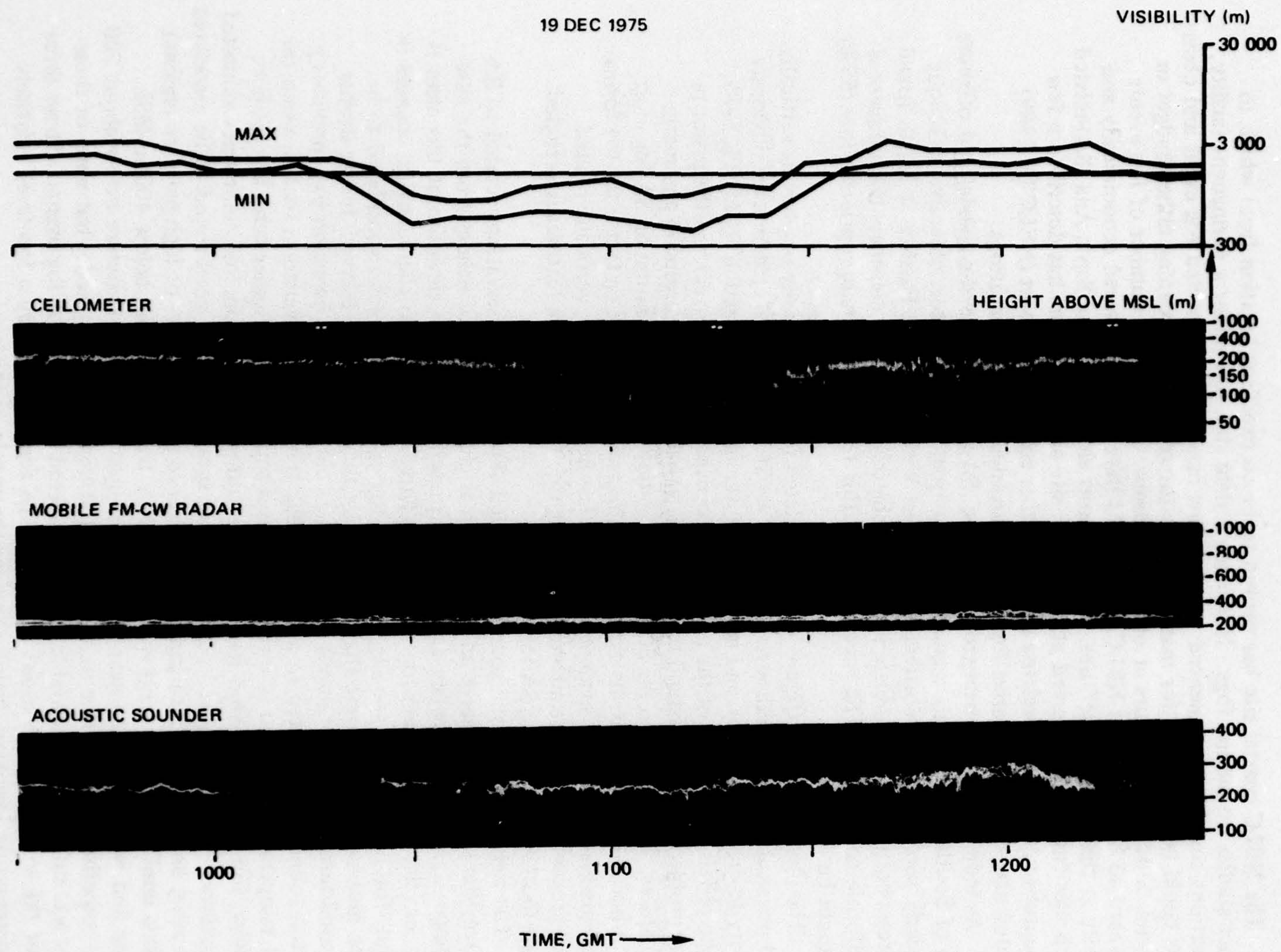

Figure 43. Sensor observations during a fog event on 19 December 1975. The ceilometer output was recorded by a new filming technique (see NELC TR 1989).

DISCUSSION AND SUMMARY

The NELC coastal site has proven to be an excellent location from which to conduct studies on marine fogs. Not being a field site, but rather a permanent facility, observations could be commenced within a few hours of an expected fog event and observations could be continued for many hours without unduly burdening either budget or personnel, which often occurs at off-site locations. Even if the number of fog events each year had been small at NELC, they could have been monitored economically and assuredly at this "home-base" site. Many stratus cloud (SC)- and Santa Ana (SA)-related fog episodes have been observed at the NELC site and this report has described a few representative events of SA-related fog. An earlier companion report (NELC TR 1989) presented data on representative fog events associated with SC conditions.

As indicated in the background section, SA-related fog in the coastal and offshore region of Southern California appears to be unique. A four-factor, objective technique is regularly used by the forecasters at the Naval Weather Service Facility at North Island to forecast both SC- and SA-related fog. The objective technique considers the uniqueness of California coastal fog. The success rate of this technique is inappropriately low (53%) and should be improved.

The physical model (figure 7) for SC-related fog was primarily one having vertically related physical processes, although horizontal variations of several elements are obviously necessary to create, maintain, and modify the inversion. As reported in NELC TR 1989, the basic physical processes of the model were concluded to be correct and the major remaining problem is to understand the mesoscale variability of the inversion and marine layer features. In contrast to the SC fog investigation, this investigation on SA fog must consider horizontal or mesoscale variations as the primary controlling factor for fog formation and dissipation because evidence indicates less dependence on vertically related physical processes. Thus less information on marine fog formation features is expected from the local sensors during SA fog episodes.

The radar and acoustic sounders revealed three major observations related to SA fog. One, the sounders observe an echo which is characteristic of echoes from the base of a temperature inversion when an SA fog is present. Two, the elevation of this echo is usually less than 400 m when fog is present. Three, there are no characteristic changes in the echo structure prior to, during, or after a fog episode. The echo considered to be near the inversion base is somewhat less definite then the echo observed during stratus cloud conditions. Semicontinuous or indefinite echoes near the inversion base previously have been found to be related to relatively weak temperature inversions; that is, when the vertical temperature gradient is small. This echo sometimes had other echo layers above and below, sometimes appeared to have sudden jumps in elevation, and sometimes exhibited substructures. Variable, layered echo structures sometimes have been found to be associated with moving or changing convergence or divergence systems (low- or high-pressure regions). When this semi continuous echo was temporarilly traceable, it was below 400 m MSL elevation and was most often near 200 m. Changes in the echo structure below about 700 m were sometimes noted prior to, during, and after an SA fog episode, but none of these changes was sufficiently repeatable to be considered related to SA fog events. These three facets of the sounder observations imply that SA fog is capped by a low-level, relatively weak temperature inversion during changing mesoscale conditions.

The analysis of the 13 December 1974 SA fog showed that mesoscale features primarily were controlling the fog event. These mesoscale "eddies" were, of course, responding to the large-scale synoptic pattern which ultimately must be understood to

predict the mesoscale pattern. The movement of the low-level fog deck and the variability in the visibility for closely spaced stations attest to subtle mesoscale control. The great variability of the visibility at one site during fog episodes suggests that a highly variable turbulence structure is present in the layer below the temperature inversion. This might be expected near moving mesoscale features beneath weak capping inversions.

Variations in sea-surface temperature (SST) patterns and strong gradients of SST should affect SA fog formation and dissipation but SST patterns were not examined in this study.

In his development of the four-factor fog prediction technique (discussed in FOG FORECASTS AT NORTH ISLAND), Leipper (1968)[12] stressed the importance of the low-level inversion and its change with time, the SST, and the existing moisture content in the surface layer. He stressed the need to examine the changes in the temperature and humidity structure over the coast, which should provide clues on the mesoscale changes over the ocean. This was based on a two-dimensional (east-west and vertical coordinates) mesoscale model which contains an interplay between moisture content, vertical distribution of the moisture, radiational cooling at the top of the fog, the capability of the subsiding SA winds to "push" the marine layer away from the coast, and the offshore cool region of upwelled water. There is no reason to suspect that these factors are not the major ones in SA fog conditions. This study supports his major contentions.

Leipper also discussed the physical basis for the fog-forecasting indices used daily at North Island. He showed how changes in the atmospheric temperautre structure from the surface up to the 700-millibar level (~3 km) provides clues on SA fog-conducive situations. Figures 44, 45, and 46 show the changes in the temperature structure below 1.5 km and the surface temperature at 1600 PST for several days, spanning fog events with somewhat rapid onsets as discussed in this paper. Leipper indicates that a low inversion and low (relative) surface temperature would generally precede an onset of fog. The changes in the atmospheric temperature structure and the surface temperatures shown in figures 44, 45, and 46 do not show a trend relative to the onset time of the sharp fog banks. This conclusion does not indicate the lack of merit in Leipper's suggested sequence of changes in the temperature structure, particularly because fog occurred on other nearby days included in the figures. The occurrence of fog events separated by only hours or a few days suggests that the fog-forming conditions were spatially distributed or rapidly created. Leipper's suggested sequence of events may be essentially correct. The mesoscale variability of the temperature and humidity structure must be the critical factors and must be more variable than originally thought.

This study has provided measurements of visibility during SA fog which show that the minimum visibilities are almost always less than the minimum visibilities encountered during SC fog. This supports earlier studies and the contention that continental aerosols must be present in SA fogs. The air-parcel trajectory analysis for a fog event on 13 December 1974 provides strong support that continental aerosols are present in SA fogs. Direct measurements of the aerosol characteristics at NELC also indicate that continental aerosols are present in SA fog (Desert Research Institute, private communication). Other trajectory analysis should be made during SA conditions to determine the source regions of the aerosols. However, more offshore surface wind measurements are necessary to determine more reliable trajectories.

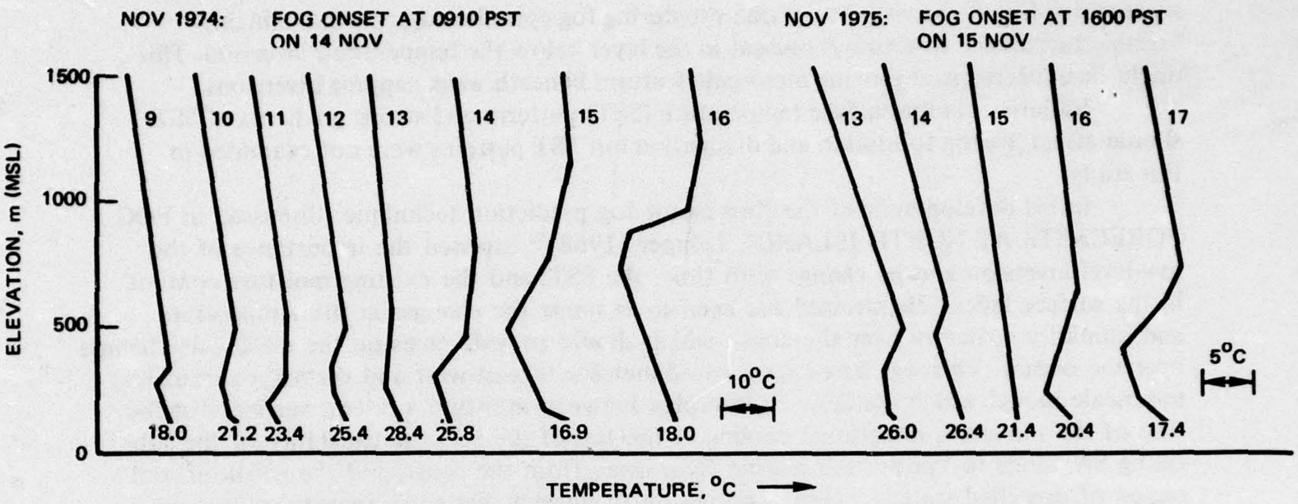

Figure 44. Vertical temperature structure at 1600 PST (2400 GMT) observed at Montgomery Field during days with fog. (The number at the bottom of each profile is the surface temperature in °C.)

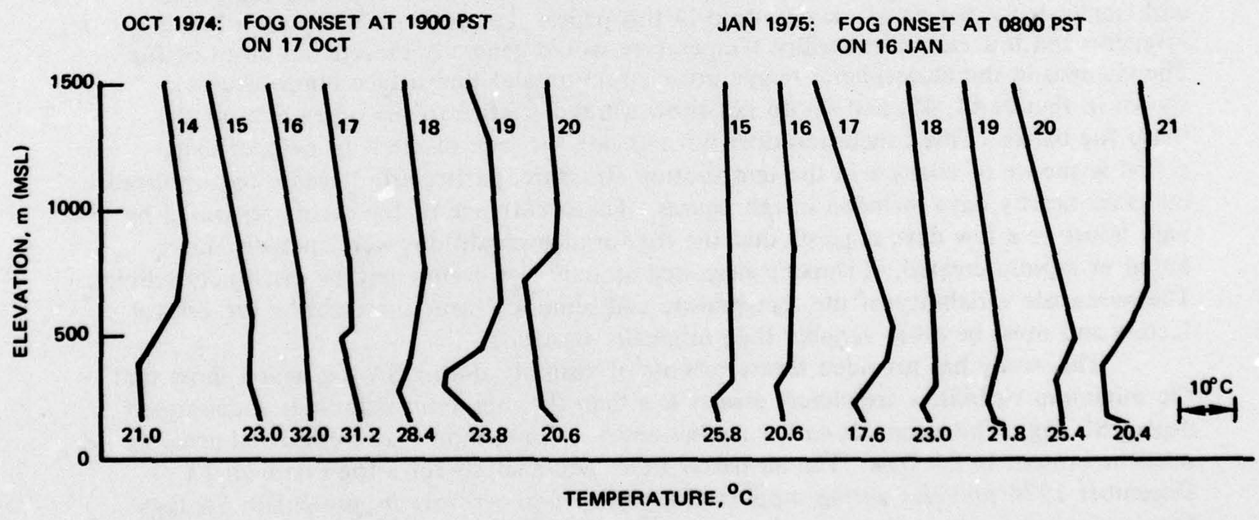

Figure 45. Vertical temperature structure at 1600 PST (2400 GMT) observed at Montgomery Field during days with fog. (The number at the bottom of each profile is the surface temperature in °C.)

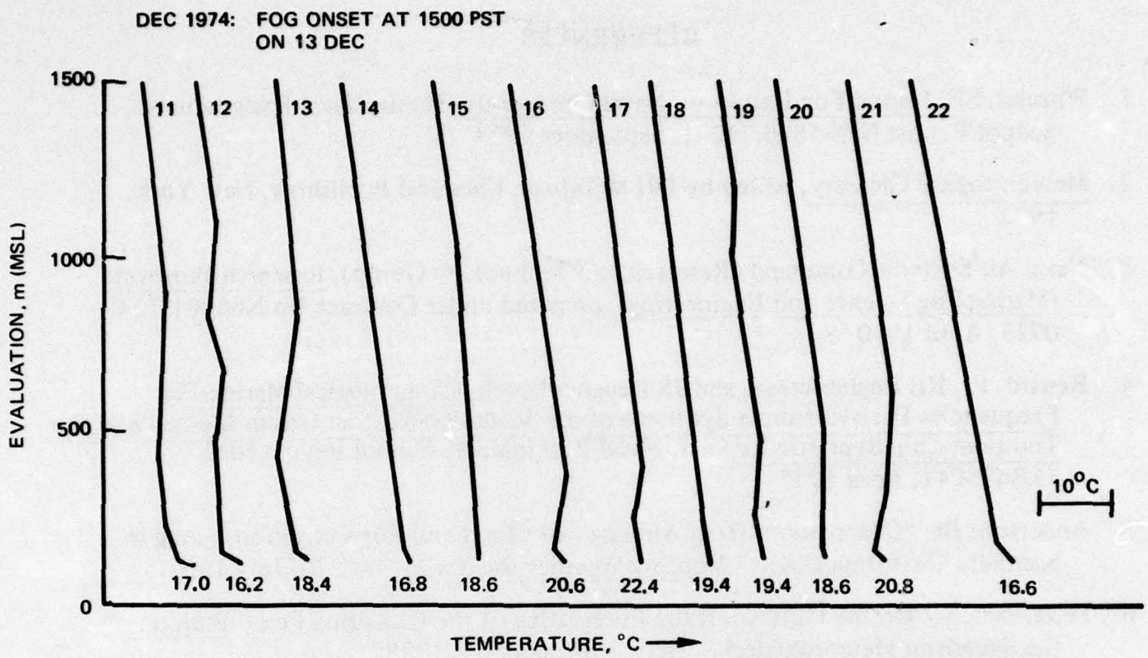

Figure 46. Vertical temperature structure at 1600 PST (2400 GMT) observed at Montgomery Field during days with fog. (The number at the bottom of each profile is the surface temperature in °C.)

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